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Older Adults: MIND YOUR STEP!

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Older Adults:
MIND YOUR STEP!

ACADEMISCH PROEFSCHRIFT

ter verkrijging van de graad

Doctor aan de Vrije Universiteit Amsterdam,
op gezag van de rector magnificus
prof.dr. V. Subramaniam,
en
Doctor in de Biomedische Wetenschappen aan de KU Leuven,
op gezag van de rector magnificus
prof.dr. R. Torfs,

in het openbaar te verdedigen
ten overstaan van de promotiecommissie
van de Faculteit der Gedrags- en Bewegingswetenschappen
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De Boelelaan 1105

door
Masood Mazaheri
geboren te Isfahan, Iran

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dr. M. Roerdink

Dit proefschrift is tot stand gekomen op basis van een daartoe tussen de Vrije Universiteit Amsterdam en de KU Leuven, België, overeengekomen samenwerkingsverband ter regeling van een gezamenlijke promotie, hetgeen mede tot uiting wordt gebracht door de weergave van de beeldmerken van beide universiteiten op deze titelpagina.

Contents

Chapter 1

Introduction

Age-related walking disorders

Walking disorders are common among older adults and often lead to activity restriction, disability and reduced quality of life. About one-third of community-dwelling older adults above the age of 70 have difficulty walking (Verghese et al. 2006). This proportion increases with advancing age. For example, beyond age 85, the percentage of people with normal gait drops to 18% (Bloem et al. 1992).

Among the intrinsic risk factors of falls, walking and balance impairments constitute the second largest category of causes of falls (Rubenstein and Josephson 2002) and the most consistent predictors of future falls in pertinent studies (Ganz et al. 2007). Falls, the leading cause of unintentional injuries among elderly, may result in loss of independence, institutionalization and death (Rubenstein and Josephson 2002). Falling, however, is only one of several devastating consequences of walking disorders in older adults. 'Idiopathic senile gait disorder' has also been associated with increased risk of cardiovascular death (Bloem et al. 2000). This suggests that age-related changes in walking should be considered a sign of preclinical disease (Bloem et al. 2000). Walking disorders also predict future development of non-Alzheimer dementia (Marquis et al. 2002) and walking disturbances are even associated with risk of death in older adults (Wilson et al. 2002). Studenski et al. (Studenski et al. 2011) found that slower walking speeds are associated with shorter life expectancy. Walking disorders serve as predictor for survival not only because they are indicators of dysfunction in different organs such as musculoskeletal, cardiovascular or neurocognitive system but also because they lead to reduced physical activity, which has a direct effect on survival (Studenski et al. 2011).

Walking in older adults is less coordinated, more conservative and less flexible than healthy walking in young adults (Rubenstein and Josephson 2002). Compared with young adults, older adults demonstrate a 17%-20% reduction in walking speed, accompanied by decreased stride length and increased double-support stance duration (Winter et al. 1990; Elble et al. 1991). Another age-related change in walking is the increase of step width. Winter et al. (Winter et al. 1990) attributed these age-associated changes to an adaptive behavior resulting in a safer (less destabilizing) gait pattern with a reduced chance of falling. On the other hand, these changes may also indicate mobility limitations, which may be associated with an increased risk of falling (Ko et al. 2009).

A first and necessary step to understand the mechanisms underlying walking disorders in older adults is to identify the requirements that should be fulfilled by the locomotor system. Based on a tripartite model of walking (Grillner and Wallen 1985; Patla and Shumway-Cook 1999; Balasubramanian et al. 2014) (Figure 1-1), these components include adaptability, balance and stepping. This thesis focuses on the first and second component of this model, walking adaptability and balance, which are examined in relation to the attentional demands of walking.

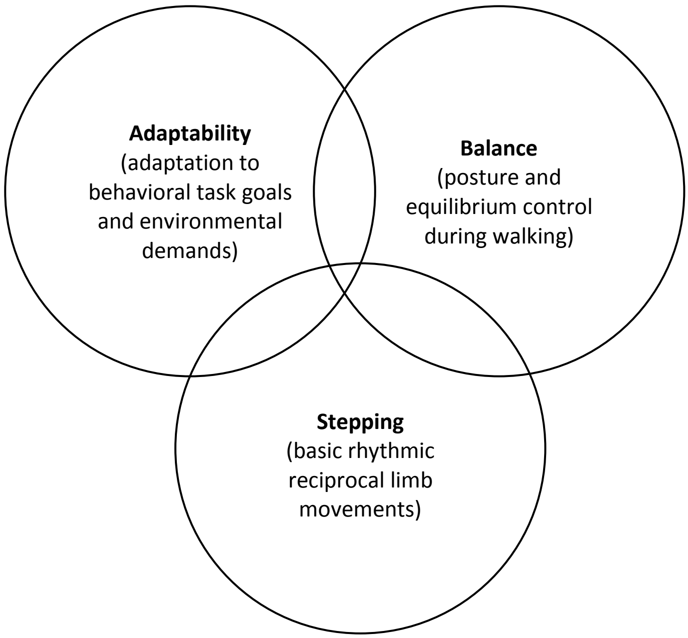

Figure 1-1. Tripartite model of locomotor control: adaptability, balance and stepping (adapted with permission from Balasubramanian et al. 2014:591013).

Cognitive contributions to gait

Multiple factors, such as muscle weakness, visual disorders, vertigo and postural hypotension have been identified as causes of walking disorders in older adults (Salzman 2010). However, causes of walking problems are not limited to biophysical factors. Age-associated walking disorders have also been attributed to a decline in cognitive abilities (Yogev-Seligmann et al. 2008). Current evidence suggests that, in contrast to traditional views, walking should not be considered an automatic motor activity involving a minimal use of attentional resources (Lajoie et al. 1993; Woollacott and Shumway-Cook 2002). Instead, walking is an attentionally demanding process. When one or more tasks are performed concurrently with a walking task (i.e., during dual tasking), they compete for the available attentional resources. In this situation, task performance may decrease due to either:

(1) Increased *attentional costs*. According to the capacity sharing theory (Kahneman 1973), attentional resources are limited. The more demanding a particular task, the more resources are required. If the combined task performance demands exceed limited attentional resources, then the performance of the walking task, the concurrent task, or both,

deteriorate. Due to a decline in cognitive resources, such attentional limitations prevail in older adults.

(2) *Task prioritization*. Dual-task decrement can also happen due to a trade-off between attentional resources, due to priority being given to one task over the other (Bloem et al. 2001; Bloem et al. 2006; Schaefer et al. 2015). In contrast to the 'posture-first' principle, in which priority is given to the walking task over the concurrent task in challenging conditions, people may sacrifice their walking performance in order to optimize their concurrent task performance. Failure to adhere to the 'posture-first' principle in difficult multitask conditions is associated with increased risk of falling (Bloem et al. 2006; Schaefer et al. 2015).

Attention is a subcategory of executive function. Executive function is an umbrella term for the control of cognitive processes including volition, self-awareness, planning, response inhibition, response monitoring and attention (Yogev-Seligmann et al. 2008). During walking, executive function is involved in flexible adaptation of the gait pattern, especially when walking in complex environments. Indeed, poor and intermediate executive function in healthy older adults is associated with decreased performance when walking on an obstacle course (Ble et al. 2005), highlighting the importance of executive function for walking under challenging conditions. Strong association of executive function and walking-task performance has been shown in elderly non-demented fallers when walking is performed with a concurrent task, but not under regular walking conditions (Springer et al. 2006).

Although it is clear that walking is an attention-demanding task and that the attentional demands increase with aging, little is known about how attention is allocated to specific subprocesses. Note that in the original formulations of the tripartite model, attentional demands (Patla and Shumway-Cook 1999) and dual tasking (Balasubramanian et al. 2014) have been addressed as explicit subcategories of adaptability. Since the present thesis investigates how the subcategories balance and adaptability impact on attentional demands, we decided to use 'attention' as an overarching term embracing all components of locomotor control (Figure 1-2).

Adaptive stepping during walking

Walking disorders in older adults are not limited to impairments of stereotyped rhythmical gait patterns (i.e., 'stepping' in the tripartite model). Older adults often experience difficulty in walking when confronted with environmental hazards such as cluttered terrains, obstacles, curved or slippery paths. The fact that a significant proportion of falls in older adults occurs due to trips, slips or misplaced steps (Berg et al. 1997) underscores the reduced ability to negotiate such environmental constraints. Successful performance in these challenging circumstances necessitates something more than stereotyped, rhythmical gait ('stepping'). It requires walking adaptability or "the ability to modify walking to meet behavioral task goals and demands of the environment" (Balasubramanian et al. 2014).

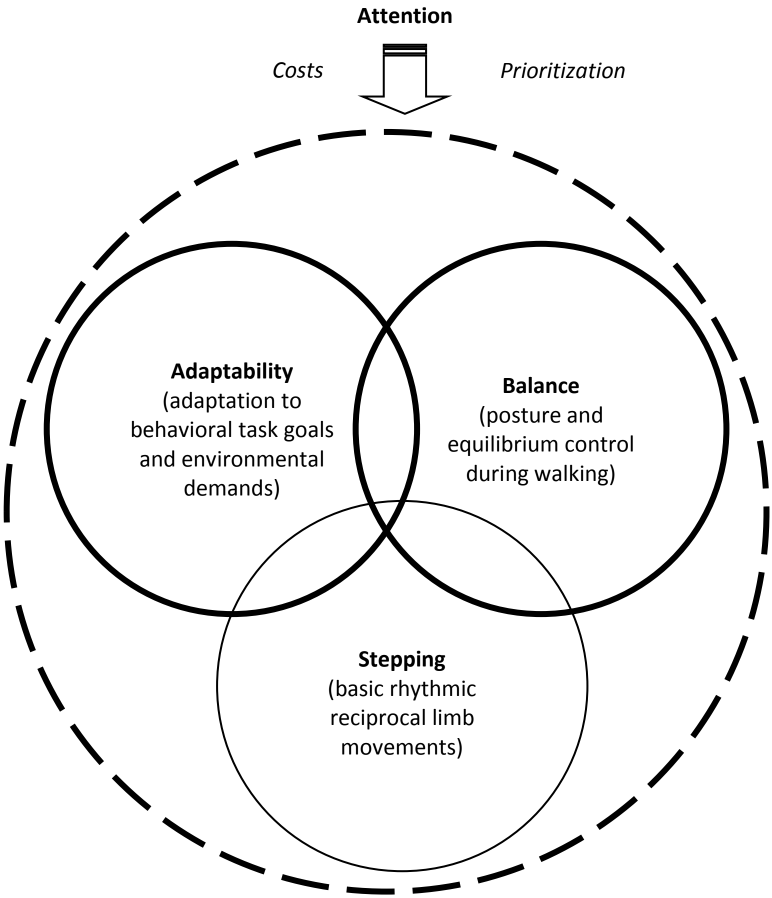

Figure 1-2. The present study focuses on the relation between attention and the first two components of the tripartite model of locomotor control, i.e., adaptability and balance.

In order to successfully adapt walking to challenging circumstances, sensory information is required. In particular, vision is essential to walking adaptability because it is necessary to register environmental challenges and to guide the feet to precise locations in the environment (Chapman and Hollands 2006; Chapman and Hollands 2007). The visual system gathers information from the near and far environment and uses it to regulate gait on both a local level (step by step basis) and a global level (navigation, route planning). Visual perception of the environment is essential for employing avoidance strategies and accommodation strategies to adjust to different surfaces in the path of travel (Patla 1997).

To evaluate walking adaptability, visually guided walking has been investigated in relation to tasks such as obstacle avoidance and precision stepping. For the latter task, walking adaptability has been evaluated in terms of accuracy of stepping onto either irregularly spaced stepping targets (Houdijk et al. 2012) or shifted stepping targets (Bank et al. 2011; Young and Hollands 2012; Hoogkamer et al. 2015). The latter situation requires step adjustments by redirecting the foot trajectory to the new target. Such step adjustments appear to be affected with increasing age. Older adults make smaller step adjustments in response to sudden shifts of stepping targets compared to young adults (Young and Hollands 2012). There is also an association between step adjustment and risk of falling (Young and Hollands 2012).

Adaptive stepping is attentionally demanding. This has been shown in several studies in which attentional costs were assessed in relation to obstacle avoidance (Siu et al. 2008; Hegeman et al. 2012; Plummer-D'Amato et al. 2012). Increased attentional costs of walking have also been demonstrated when people were required to step onto visual stepping targets (Peper et al. 2012). The research in this direction is expanded in the present thesis by studying adaptive stepping using both (ir)regular sequences of stepping targets and suddenly shifted stepping targets.

Balance control during walking

Human walking is intrinsically unstable in lateral direction (Donelan et al. 2004). Single-limb support durations constitute 70%-80% of the whole gait cycle, during which the center of mass moves forward and outside the base of support, leading to instability, particularly in mediolateral direction (Woollacott and Tang 1997). Older adults appear to have more difficulty in preserving lateral stability during walking than young adults (Kaya et al. 1998; Lee and Chou 2006). Active control needed to sustain mediolateral stability, particularly in older adults, may increase attentional costs of walking. However, only few studies have specifically examined the contribution of balance control to the attentional costs of walking. Evidence for attentional costs of balance control has mostly been inferred from studies manipulating the base of support, or from studies comparing the attentional costs of walking to tasks like sitting or standing, or the attentional costs of single-support to double-support stance phases during walking (Sajiki et al. 1989; Lajoie et al. 1993; Lajoie et al. 1996; Peper et al. 2012). These studies reported increased attentional costs from sitting to standing to walking (Lajoie et al. 1993; Lajoie et al. 1996; Peper et al. 2012), but attentional costs for the different support phases during walking varied inconsistently over studies (Sajiki et al. 1989; Lajoie et al. 1993). Importantly, none of these studies have systematically manipulated balance demands during walking rendering it difficult to draw any firm conclusions regarding the effect of balance control requirements on the attentional costs of walking.

In this thesis attentional demands of adaptive walking and balance control are addressed using a dual-task paradigm. In the next section, this paradigm is briefly introduced, followed by an explanation of the specific methodological choices for the current research.

Using dual tasking to assess attentional aspects of walking

Dual tasking has become the standard method to examine the relationship between attention and motor activities (Woollacott and Shumway-Cook 2002; Fraizer and Mitra 2008) and, as such, this method has also been applied to determine the attentional costs of posture and gait.

When dual tasking is used to investigate attentional costs of walking, participants typically are instructed to prioritize the walking task (Woollacott and Shumway-Cook 2002). In this situation, limited attentional resources are available for the secondary task, implying that changes in performance of this non-prioritized task reflect the attentional costs of walking. To be able to interpret the change in secondary task performance as an indication of the attentional costs of walking, it is important to make sure that the walking task performance remains constant under dual-task conditions compared to the baseline (single-task) condition. Walking task performance can be held relatively constant when a probe reaction-time task is used as the secondary task (Lajoie et al. 1993; Lajoie et al. 1996; Sparrow et al. 2002). In a probe reaction-time task participants should react, by means of a vocal or manual response, to stimuli as soon as possible. By employing probe reaction-time tasks with auditory or vibratory stimuli the possibility of structural interference with walking task can be kept to a minimum. This is why in the current studies vibratory stimuli were used, in combination with manual responses, to assess the attentional costs of adaptive walking (Chapters 2 and 3).

When dual tasking is used to investigate the effects of an attentionally demanding cognitive task on walking performance, participants may be instructed to give equal priority to both tasks. Attentional demands of cognitive tasks and the extent to which these tasks introduce resource interference with walking are two major concerns in the selection of cognitive tasks. Bock (Bock 2008) studied the effect of concurrent task characteristics on the emergence of dual-task interference. He compared the effects of many different tasks, and concluded that particularly those that involved continuous visual monitoring are detrimental for walking performance. The auditory Stroop task is an attention-demanding task that does not involve such visual monitoring. Moreover, it is associated with an important other executive function factor, namely response inhibition. This is why this task has been used in the present thesis to examine how cognitive load affects reactive step-adjustment performance (Chapter 4). The auditory Stroop task has been widely used in studies of obstacle avoidance (Weerdesteyn et al. 2003; Hegeman et al. 2012) but not for other forms of adaptive stepping.

Outline of the thesis

Although the incorporation of cognition in gait assessment and treatment programs is recommended in the literature (Lord and Rochester 2007), little is known about how attentional aspects are related to walking adaptability and balance control, especially in older adults. This is why this thesis focuses on the effects of age, adaptive stepping and balance control on attentional costs of walking and on the effects of age on task prioritization during adaptive walking tasks with concurrent performance of an auditory Stroop task. Gaining insight into such relationships may help understand why walking adaptability and balance control are impaired in older adults, particularly when they have to divide their attention between walking and a concurrent task. Such insights may also contribute to improving dual-task training paradigms for older adults.

Chapter 2 addresses the **effects of age and executive function on attentional costs of visually guided adaptive walking**. Young adults and older adults with higher and lower executive function were required to walk at their preferred walking speed on an instrumented treadmill equipped with a force platform and a projector. The force platform allowed online detection of gait events and gait characteristics and the projector allowed projection of (visual) stepping stones onto the treadmill belt. The stepping stones were adjusted to participants' own gait pattern. Attentional costs of walking were measured using a vibrotactile probe reaction-time task in three walking conditions: uncued normal walking, walking onto a series of regularly spaced stepping stones and walking onto a series of irregularly spaced stepping stones. Participants were asked to give priority to the walking task. We hypothesized that cued walking, especially walking onto irregularly spaced stepping stones, impose higher attentional costs than uncued walking. We expected this effect to be more pronounced in older adults, particularly in those with lower executive function.

Based on the suggestion proposed in Chapter 2 that attentional costs of walking may have been influenced by variation of balance demands, the **effects of age and balance demands on attentional costs of walking** were investigated in Chapter 3. Lateral balance demands were manipulated by means of walking with a narrow step width[1] (increasing balance demands) and walking with an external stabilization device (decreasing balance demands). Young and older adults walked with their preferred walking speed on a treadmill in five conditions: unconstrained walking; walking onto projected visual lines adjusted to either the participant's preferred step width or 50% of this preferred step width; and walking with an external stabilization device with low or high levels of stiffness. Similar to the first experiment, attentional costs were measured using a probe reaction-time task and participants were required to prioritize the walking task. We expected that lower balance demands would reduce the attentional costs of walking, whereas higher balance demands would increase the attentional costs. We also expected these effects to be more pronounced in older adults.

In Chapter 4, the **effects of age and dual tasking on step adjustments to sudden target shifts in visually cued walking** were addressed to assess the way in which stepping performance was affected and how the components were prioritized. Young and older adults were required to perform sudden step adjustments with and without concurrent performance of an auditory Stroop task, which served as a concurrent attentionally demanding task. A treadmill instrumented with a force platform and projector allowed to project stepping stones adjusted to each participant's gait pattern. While walking at 3 km/h, participants performed visually guided step adjustments in response to unexpected shifts of stepping stones in different directions and with different levels of task difficulty. Participants were instructed to give equal priority to both tasks. It was hypothesized that dual tasking has a detrimental effect on the step adjustments, particularly so in older adults.

In the **general discussion**, presented in Chapter 5, the main findings are discussed in relation to the (modified) tripartite model of locomotor control (Figure 1-2), followed by an outlook for future research.

[1] The data collected for the two imposed step-width conditions were also used in another study to examine the effect of narrow-base walking on mediolateral center-of-mass excursions and margins of stability in young and older adults (Arvin et al. 2016).

Chapter 2

Effects of age and executive function on attentional costs of visually guided adaptive walking

Mazaheri M, Roerdink M, Bood RJ, Duysens J, Beek PJ, Peper CE. Attentional costs of visually guided walking: Effects of age, executive function and stepping-task demands. Gait Posture 2014;40:182-6.

ABSTRACT

During walking, attention needs to be flexibly allocated to deal with varying environmental constraints. This ability may be affected by aging and lower overall executive function. The present study examined the influence of aging and executive function on the attentional costs of visually guided walking under different task demands. Three groups, young adults (n=15) and elderly adults with higher (n=16) and lower (n=10) executive function, walked on a treadmill in three conditions: uncued walking and walking with regular and irregular patterns of visual stepping targets projected onto the belt. Attentional costs were assessed using a secondary probe reaction time task and corrected by subtracting baseline single-task reaction time, yielding an estimate of the additional attentional costs of each walking condition. We found that uncued walking was more attentionally demanding for elderly than for young participants. In young participants, the attentional costs increased significantly from uncued to regularly cued to irregularly cued walking, whereas for the higher executive function group, attentional costs only increased significantly from regularly cued to irregularly cued walking. For the lower executive-function group, no significant differences were observed. The observed decreased flexibility of elderly, especially those with lower executive function, to allocate additional attentional resources to more challenging walking conditions may be attributed to the already increased attentional costs of uncued walking, presumably required for visuomotor and/or balance control of walking.

INTRODUCTION

Accurate foot placement, especially under challenging environmental conditions, is essential to prevent slips, trips or misplaced steps that are common causes of falls in elderly individuals (Berg et al. 1997). Various intrinsic factors contribute to successful stepping performance, including higher-level cognitive functions, such as attention (Lajoie et al. 1993). Assessing residual processing capacity during visually guided walking helps to reveal the amount of attention required for accurate stepping. Excessive cognitive effort invested in foot placement can limit an individual's ability to attend to environmental hazards leading to increased fall risk. Dual-task paradigms have demonstrated that increased age is associated with greater attention allocation to foot placement during walking (Lajoie et al. 1996), particularly in elderly individuals with a higher risk of falling (Lundin-Olsson et al. 1997).

While the ability to adapt stepping behavior has been assessed in relation to various environmental constraints such as an obstacle (Hegeman et al. 2012) or a curb (Wellmon et al. 2013), other studies have exploited visual or auditory cues to assess gait adaptability, especially in neurological (Roerdink et al. 2009), orthopedic (Houdijk et al. 2012) and geriatric (Bank et al. 2011; Peper et al. 2012) populations. Compared to uncued walking, attentional costs increased when steps were adjusted to external cues, with visual cues (projected stepping stones) demanding more attention than auditory cues (metronome beeps) (Peper et al. 2012). This result indicates the predominant role of visual information in gait control, particularly in environments that demand visually guided step adjustments (Beurskens and Bock 2013).

Several factors may influence the relationship between visually guided step adjustments and associated attentional demands. To unravel the effect of age on this relationship, Peper et al. (Peper et al. 2012) examined the attentional demands of visually cued walking in young and elderly adults. The attentional demands were higher for elderly participants for all cued and uncued conditions, but the increase in attentional demands over the conditions was comparable for both age groups. In addition, decreased functioning of specific cognitive domains, such as executive function (EF) (Hausdorff et al. 2008) may affect age-related deficits in attentional demands of walking. EF represents coordinated action of cognitive processes such as attention, planning, response monitoring and response inhibition, and is essential for successful performance of goal-directed activity in a flexible manner (Yogev-Seligmann et al. 2008). Impairment of one or more of these processes may decrease the ability to efficiently deal with changes in walking task demands (Yogev-Seligmann et al. 2008). Indeed, EF is a predictive factor for fall risk among older adults (Holtzer et al. 2007) and is associated with stepping performance, particularly under increased environmental complexity (Persad et al. 2008). A third important factor in visually guided stepping is terrain complexity (Beurskens and Bock 2013). Visually guided stepping becomes less accurate with increased environmental complexity (Houdijk et al. 2012) and this difference is more prominent in elderly individuals (Lindemann et al. 2013).

To date, the role of age, EF, and terrain complexity in visually guided walking has mostly been studied in relation to stepping performance (Persad et al. 2008; Houdijk et al. 2012; Lindemann et al. 2013). In the current study we focused on how these factors influence the attentional demands of visually guided walking. To this end, we recruited elderly participants (considerably older than those in (Peper et al. 2012)) with lower EF (LEF) or higher EF (HEF) and a group of young adults. Because attentional demands of walking appear to be minimal at one's preferred speed and gait pattern (Kurosawa 1994; McFadyen et al. 2009), all participants walked at their self-selected comfortable walking speed under three conditions: uncued walking and walking onto regular and irregular patterns of stepping targets, with the patterns of stepping targets being based on each individual's preferred gait pattern. In this way we created comparable conditions for all participants. We used a probe reaction time (RT) task to assess the associated attentional demands and hypothesized that RT would be higher for cued than uncued walking, in particular when the stepping stones were irregularly spaced. These differences were expected to be larger for elderly participants, especially for those with LEF, compared with young participants. In line with previous findings (Lajoie et al. 1996), we also expected higher attentional costs for elderly groups compared to young participants for uncued walking. Furthermore, visually guided stepping was hypothesized to be less accurate for walking onto an irregular than a regular sequence of stepping targets, again most markedly so for older adults and particularly those with LEF.

MATERIALS AND METHODS

Participants

Fifteen young adults and two groups of elderly adults with either HEF (n=16) or LEF (n=10) participated (see Table 2-1). Exclusion criteria were self-reported cardiovascular or cardiopulmonar problems, orthopedic conditions, uncorrected visual or auditory impairments, neurological disease, other conditions limiting mobility, use of walking aids and Mini Mental State Exam (MMSE) score below 19 (actual scores all ≥26; Table 2-1). The older adults were selected from a cohort of 148 elderly who had previously participated in the Fall Risk Assessment in Older Adults (FARAO, MOVE Research Institute Amsterdam). We invited participants based on their Trail Making Test (TMT) B/A score (Hester et al. 2005), using the upper and lower 33% thresholds to select participants for the LEF (B/A>2.78) and HEF (B/A<1.91) groups, respectively. The experimental protocol was approved by the local ethics committee and participants signed informed consent before the experiment commenced.

Table 2-1. Participants' characteristics per group

	Young adults (n=15)	Elderly adults (n=25)		Group comparisons	
		Higher EF* (n=15)	Lower EF (n=10)	Statistics**	*p*-value
Age (yr)	22.7 (2.5)	76.0 (6.6)	74.5 (7.5)	$F_{2,37}$=399.30	<0.001
Height (m)	1.77 (0.10)	1.69 (0.08)	1.70 (0.06)	$F_{2,37}$=3.92	0.03
Weight (kg)	72.3 (11.7)	68.7 (8.3)	72.9 (9.3)	$F_{2,37}$=0.73	0.49
Sex (female/male)	8/7	11/4	5/5	$X^2(2)$=1.81	0.40
MMSE	-	29.1 (1.0)	28.8 (1.6)	$t(23)$=0.51	0.62
Executive function					
TMT					
Part A (s)	20.9 (5.2)	42.9 (11.1)	43.2 (11.9)		
Part B (s)	42.3 (11.5)	76.7 (28.9)	103.1 (34.9)		
B/A ratio	2.04 (0.39)	1.76 (0.34)	2.43 (0.64)	$F_{2,37}$=6.53	<0.01
SCWT interference (s)	26.1 (9.0)	49.1 (17.5)	72.1 (38.2)	$F_{2,36}$=12.17	<0.001
Timed Up & Go (s)	-	8.7 (2.4)	9.0 (1.5)	$t(23)$=-0.32	0.75
Comfortable walking speed (km/h)	4.3 (0.4)	3.4 (0.7)	2.9 (0.9)	$F_{2,37}$=13.10	0.001
Baseline reaction time (ms)	265.4 (49.1)	367.2 (84.1)	325.7 (73.5)	$F_{2,37}$=7.99	0.001

Notes: Values are mean (SD) unless stated otherwise. TMT = Trail Making Test; SCWT = Stroop Color-Word test.
* Data of one person in HEF group were removed in view of outliers in ΔRT performance.
**Overall group effects, consisting of 2 levels for MMSE and Timed Up & Go and 3 levels for all other outcome measures

Instrumentation

An instrumented treadmill with an embedded force platform (ForceLink, Culemborg, The Netherlands) allowing for online detection of gait events and gait characteristics (Roerdink et al. 2008) was used in all experimental walking conditions. A sequence of stepping targets (length: participant's shoe length, width: 10 cm) could be projected onto the treadmill, approaching the participant at belt speed. Thanks to a 1.2 m projection board attached to the front of the treadmill, several upcoming steps were visible to the participant (Figure 2-1). Stimulus-response RT was assessed using a custom-made stimulus vibrator (pulse duration: 300 ms, attached to the non-dominant hand's wrist) and a response button (sampling rate: 1000 Hz, held in the dominant hand). All participants wore a safety harness while walking on the treadmill.

Pre-experimental procedure

All participants first practiced treadmill walking at various speeds for approximately 7-10 min, depending on their prior experience. Subsequently, participants were familiarized with walking onto a sequence of regularly and irregularly spaced stepping targets while concurrently performing the RT task. Familiarization continued until the participant fully

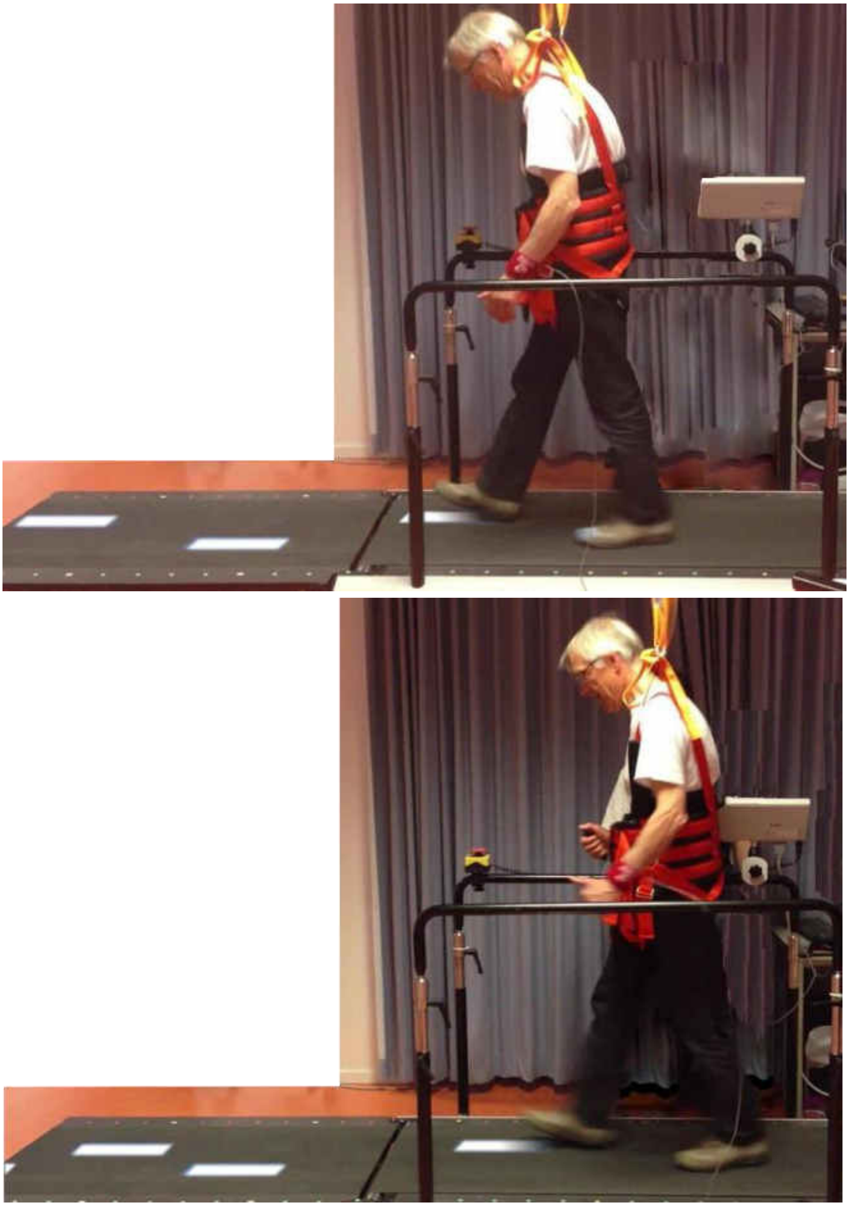

Figure 2-1. Instrumented treadmill with regular (upper panel) and irregular (lower panel) patterns of projected stepping targets.

understood the experimental tasks. Next, the participant's comfortable walking speed (CWS) was determined by taking the average of two self-reported comfortable walking speeds as obtained by gradually increasing and subsequently decreasing belt speed (0.1 km/h steps; starting considerably slower and faster than preferred, respectively). All experimental walking conditions were performed at the participant's CWS.

Experimental protocol

First, all participants performed the TMT (using printed versions of parts A and B; (Hester et al. 2005)). Elderly participants further performed the timed up-and-go (TUG) test, a standard functional mobility test.

The experiment involved two blocks comprising three walking conditions (uncued walking, regularly cued walking, and irregularly cued walking). Each block contained one trial per condition, presented in random order. Sufficient rest between trials was allowed to reduce fatigue. Each trial consisted of 130 strides and lasted approximately 2.5 min, depending on participant's cadence and walking speed.

For uncued trials, participants were informed that no visual cues would be presented. In cued trials, stepping targets were presented to cue both left and right footfalls. Participants were instructed to place their feet as accurately as possible on the stepping targets. In regularly cued trials, the sequence of stepping targets was regularly spaced, matching the participant's preferred step width and step length (as determined online over 8 steps of uncued walking at the beginning of each trial). In irregularly cued trials, the anterior-posterior distance between stepping targets varied randomly by maximally 30% from the participant's preferred stride length (Figure 2-1; see also supplementary material).

Eleven vibratory stimuli were presented per trial. Participants were instructed to press the response button as soon as possible after stimulus presentation, while giving priority to the walking task. Because attentional demands vary across the gait cycle (Lajoie et al. 1993), stimuli were always presented at the moment of heel strike (see (Peper et al. 2012) for details), with a random 5-10 s inter-stimulus interval. Participants also performed the RT task while sitting on a chair (10 s inter-stimulus intervals), yielding baseline values for each individual. These baseline trials were performed prior to the first block and after the second block of walking trials.

At the end of the experiment, participants performed the Stroop Color-Word Test (SCWT, Hammes version; another EF indicator (Van der Elst et al. 2006)), for which they had to name words (subtask 1), colors (subtask 2) and ink color of printed words (subtask 3) as quickly (timed with a stopwatch) and accurately as possible.

Data analysis

Due to incorrect task performance, the data of one HEF participant were excluded from further analysis. RT was defined as the temporal interval between stimulus and response onsets. The first stimulus served as warning signal and was excluded from analysis. We discarded 32 stimulus-response pairs (i.e., <1%; 7 for HEF, 20 for LEF, 5 for young adults) because RTs fell outside the 120-1100 ms range, representing thresholds for anticipation and loss of attention, respectively (Schmidt 2005). The number of discarded responses increased from baseline (n=0) to uncued (n=8), regularly cued (n=11), and irregularly cued (n=13) conditions. The medians of the remaining RTs per trial were averaged over the two trials per condition. To eliminate individual baseline differences, baseline RT was subtracted from the RTs obtained for the walking conditions, yielding ΔRT.

For each cued walking trial, stepping accuracy was quantified by the standard deviations of the anterior-posterior (SD_{AP}) and medio-lateral (SD_{ML}) distance between the center of the stepping stone and the corresponding center-of-pressure position at mid-stance (Houdijk et al. 2012), with lower values indicating a lower variable stepping error (i.e., higher stepping accuracy). The first nine footfalls were discarded and a median filter (median±3×SD) was applied over the remaining distances to remove outliers. SD_{AP} and SD_{ML} were averaged over the two trials per condition.

To remove the motor and perceptual components of the TMT, the B/A ratio score was adopted as EF index (Hester et al. 2005). The SCWT interference score was obtained by taking the average of the time needed for subtasks 1 and 2 and subtracting this from the time required for subtask 3 (Valentijn et al. 2005).

Statistical analysis

Between-group differences for age, weight, height, CWS, B/A ratio, SCWT interference score and baseline RT were assessed using one-way analyses of variance (ANOVAs). Independent *t*-tests were used to compare MMSE and TUG among groups, and a Chi-square test for gender. ΔRT was analyzed using a 3 (group: young adults, HEF elderly, LEF elderly) × 3 (task: uncued, regularly cued, irregularly cued) mixed-model ANOVA with group as between-subject factor and task as within-subject factor.[2] Furthermore, one-sample t-tests were used to test if ΔRTs were different from 0. A 3 (group) × 2 (pattern: regular, irregular) mixed-model ANOVA with pattern as within-subject factor was applied to SD_{ML} and SD_{AP}. Significance was assumed for $p<0.05$. Post-hoc pair-wise comparisons involved Bonferroni correction, for interaction effects preceded by simple effects analyses.

[2] Correction for variations in walking speed (by including speed as co-variate) was undesirable, because this would counteract our control for comparable walking conditions (at CWS) in terms of attentional costs.

RESULTS

Group characteristics

Table 2-1 presents participants' characteristics for the three groups. Age, height, weight, TUG, and MMSE were similar for the HEF and LEF groups, but compared to young participants age was higher in both elderly groups and height was lower in the HEF group. Regarding EF, the HEF group scored better than the LEF group on both the TMT (B/A ratio) and SCWT, while the young participants outperformed both elderly groups on the SCWT. Young participants walked faster than both elderly groups, whereas the HEF and LEF groups did not differ. Baseline RT was higher for the elderly groups than for the young adults (the difference reaching significance for the HEF group).

Attentional demands

One-sample *t*-tests showed that ΔRT was significantly larger than 0 for all groups for all walking conditions (all t's>3.05, all p's<0.01), implying that walking required more attention than the baseline condition. The ANOVA on ΔRT yielded a significant effect of task ($F_{2,74}$=30.72, p<0.001). Post-hoc analysis revealed that attentional demands increased significantly from uncued walking to regularly cued walking to irregularly cued walking. The group x task interaction (Figure 2-2) was also significant ($F_{4,74}$=2.82, p<0.05). Post-hoc analysis showed significantly lower ΔRT values for young participants compared to both elderly groups in the uncued condition, but no between-group differences in the cued conditions. For young participants the increases in ΔRT from uncued to regularly cued to irregularly cued walking were all significant. For the HEF group, only irregularly cued walking differed significantly from the other conditions. For the LEF group, ΔRT did not differ significantly over the walking conditions.

Stepping accuracy

The effect of pattern was significant for both SD_{AP} ($F_{1,37}$=249.08, p<0.001) and SD_{ML} ($F_{1,37}$=13.55, p<0.01), with less accurate stepping for irregular than regular patterns of stepping targets (as evidenced by higher variable stepping errors; Figure 2-3). The effect of group was also significant for both SD_{AP} ($F_{2,37}$=8.75, p<0.01) and SD_{ML} ($F_{2,37}$=6.39, p<0.01). Post-hoc analyses for SD_{AP} showed that young participants placed their feet more accurately onto the stepping targets (i.e., lower SD_{AP}) than both elderly groups. Performance on SD_{ML} was also better for the young adults than for the elderly, resulting in a significant difference with the HEF group. The group × pattern interaction was not significant for either direction.

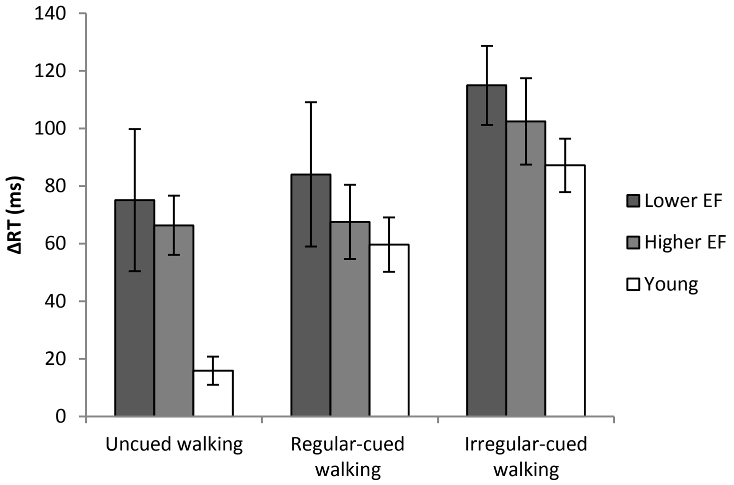

Figure 2-2. Mean ΔRT for each walking condition, presented for the three groups of participants. Error bars indicate standard error of the mean.

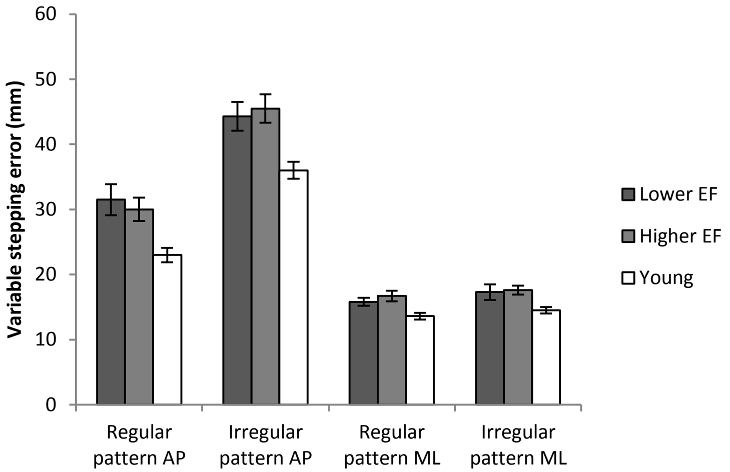

Figure 2-3. Stepping accuracy per condition for the three groups of participants. Lower variable stepping error values indicate higher stepping accuracy. Error bars indicate standard error of mean.

DISCUSSION

As expected, the attentional costs of uncued walking were significantly lower for young participants compared to both elderly groups. Moreover, cued walking, in particular stepping onto irregularly spaced stepping targets, required more attention than uncued walking. However, the effect of increased stepping-task demands on attentional costs differed between the three groups in a way that deviated from our hypothesis. Whereas in the young group, ΔRT indeed increased from uncued to regularly cued walking and from regularly cued to irregularly cued walking, this was not the case for the elderly participants. In the HEF group, ΔRT was significantly higher for irregularly cued than uncued and regularly cued walking. In the LEF group, no change in ΔRT was observed. As discussed below, these unexpected results for the elderly groups should be considered in relation to the already elevated attentional costs for uncued walking in these groups. In line with previous research (Houdijk et al. 2012; Lindemann et al. 2013), young participants stepped more accurately onto the stepping targets than elderly, and stepping was overall less accurate with irregular than with regular patterns of stepping targets. However, in contrast to our hypothesis, the latter deterioration did not increase with higher age and lower EF.

The higher ΔRT values obtained during uncued walking for elderly adults (compared to young adults) indicate age-related changes in attentional costs of walking, consistent with evidence demonstrating dual-task decrements during normal walking among elderly people (Lajoie et al. 1996). To further examine this age-related increase in dual-task costs, we examined the attentional costs of visually guided stepping. While other studies investigated vision-related attentional costs by employing secondary tasks with different levels of visual demands (Bock 2008), we manipulated the visual context of the primary task, using cues with different levels of pattern irregularity.

Interestingly, increased demands for visuomotor control invoked by the presentation of regularly spaced visual stepping targets affected ΔRT performance of the young participants but not of the elderly participants. An explanation may be found in age-related changes in the recruitment of 'reserve' attentional resources (Stern 2009) to cope with increased task demands. Neuroimaging research has indicated that older adults recruit more neural resources at lower levels of task demand – a compensatory mechanism to maximize performance – reducing their ability to further increase neural activity at higher levels of task demand, leading to decreased performance (Reuter-Lorenz PA 2008). The observed elevated attentional demands of the primary walking task in our elderly groups, in combination with reduced changes in ΔRT as a function of task demand, are consistent with this mechanism of reduced flexibility in resource recruitment. An alternative explanation in terms of inadequate prioritization (in favor of the RT task) in elderly participants seems unlikely, as the elevated ΔRT levels in these participants and the absence of a significant group × pattern interaction for stepping accuracy indicated a 'posture first strategy'.

Hence, our results suggest that, for elderly participants, the attentional costs of uncued walking were already elevated to such an extent that further allocation of attentional resources to deal with increased task demands was limited. This elevated level of attention may be associated with increased visual demands of unconstrained normal walking in older age, as demonstrated by Anderson et al. (Anderson et al. 1998). Another explanation may be found in increased balance demands from uncued walking to regularly cued walking to irregularly cued walking (Wezenberg et al. 2011). Hence, the lack of difference in attentional costs of uncued and regularly cued walking may indicate that in older age the attentional efforts for balance control during normal walking are elevated to the level that is required for regularly cued walking. To examine the attentional demands of balance control during walking, the current setup may be extended with springs for passive external stabilization of the body, to reduce the balance demands required for walking (IJmker et al. 2013).

The increased attentional costs with increased pattern irregularity obtained for the HEF elderly group and the absence of a difference in stepping accuracy between the HEF and LEF groups indicates that EF affected secondary task performance more than performance of the walking tasks, suggesting that precise foot placement can be automated to some extent. Due to increased visuomotor and/or balance demands, precision stepping may be progressively controlled via the "non-prefrontal" pathways (Reynolds and Day 2005) in elderly adults, thereby yielding little difference in stepping accuracy for the HEF and LEF groups. However, this somewhat speculative interpretation requires further investigation.

In sum, the present results showed an age-related increase in the attentional costs of uncued walking. The amount of additional attention allocated to comply with cued walking was smaller in elderly adults (particularly in those with LEF) compared to young adults. This may be related to elevated visual and/or balance requirements of walking in elderly, which may limit the allocation of additional attention in more challenging conditions.

Chapter 3

Effects of age and balance demands on attentional costs of walking

Mazaheri M, Roerdink M, Duysens J, Beek PJ, Peper CE. Attentional costs of walking are not affected by variations in lateral balance demands in young and older adults. Gait Posture 2016;46:126-131.

ABSTRACT

Increased attentional costs of walking in older adults have been attributed to age-related changes in visuomotor and/or balance control of walking. The present experiment was conducted to examine the hypothesis that attentional costs of walking vary with lateral balance demands during walking in young and older adults. Twenty young and twenty older adults walked on a treadmill at their preferred walking speed under five conditions: unconstrained normal walking, walking on projected visual lines corresponding to either the participant's preferred step width or 50% thereof (i.e., increased balance demand), and walking within low- and high-stiffness lateral stabilization frames (i.e., lower balance demands). Attentional costs were assessed using a probe reaction-time task during these five walking conditions, normalized to baseline performance as obtained during sitting. Both imposed step-width conditions were more attentionally demanding than the three other conditions, in the absence of any other significant differences between conditions. These effects were similar in the two groups. The results indicate that the attentional costs of walking were, in contrast to what has been postulated previously, not influenced by lateral balance demands. The observed difference in attentional costs between normal walking and both visual lines conditions suggests that visuomotor control processes, rather than balance control, strongly affect the attentional costs of walking. A tentative explanation of these results may be that visuomotor control processes are mainly governed by attention-demanding cortical processes, whereas balance is regulated predominantly subcortically.

INTRODUCTION

Limited ability to adjust walking to task and environmental demands increases fall risk in elderly persons (Balasubramanian et al. 2014). An important aspect of walking adaptability is the ability to cope with variations of attentional demands associated with performing secondary tasks while walking (Shumway-Cook et al. 2002; Balasubramanian et al. 2014). An age-related increase in the attentional demands of walking may hamper an individual's ability to respond to environmental hazards with potentially serious consequences. Indeed, such age-related changes are associated with less safe gait, poor mobility, increased dependence in activities of daily living and particularly increased fall risk (Lundin-Olsson et al. 1997).

The interaction between walking and attention has most commonly been assessed using dual-task paradigms in which walking is performed simultaneously with a secondary cognitive task (Woollacott and Shumway-Cook 2002). Competition for limited attentional resources between the primary and secondary task may result in interference or decrement in performance of either one or both tasks when compared with their baseline single-task performances. Lundin-Olsson et al. (Lundin-Olsson et al. 1997) showed that older adults who are not able to continue walking while talking, are more prone to falling than those who can perform the two tasks simultaneously. More recent studies (Lindenberger et al. 2000; Priest et al. 2008; Krampe et al. 2011) support increased dual-task interference with ageing, suggesting that walking is more attentionally demanding in older than in young adults.

Increased attentional costs of walking among older adults may be attributed to subtle brain impairments or disorders in the coordination of sensory and motor information required for performing complex abilities, such as balance regulation during walking. Previous research revealed that in older adults both cognitive impairments (Sheridan et al. 2003) and elevated visuomotor demands (Bock 2008; Peper et al. 2012; Mazaheri et al. 2014; Menant et al. 2014) are associated with increased attentional costs of walking. Few studies (Lajoie et al. 1993; Lajoie et al. 1996), however, have specifically addressed how balance control affects the attentional costs of walking, especially in older adults. Pertinent evidence comes primarily from experiments with base-of-support manipulations, showing that attentional costs are higher during walking than during standing or sitting (Lajoie et al. 1993; Lajoie et al. 1996; Peper et al. 2012; Mazaheri et al. 2014). Although balance requirements may change over the gait cycle, inconsistent results have been reported regarding the attentional costs for specific phases in the gait cycle (Sajiki et al. 1989; Lajoie et al. 1993; Lajoie et al. 1996). However, balance demands were never manipulated systematically during the gait cycle as a whole, which precludes drawing firm conclusions about the effect of balance control on the attentional costs of walking. In the present study, we focused on lateral stability manipulations because walking is less passively stable in mediolateral direction than fore-aft direction (Bauby and Kuo 2000). Active sensorimotor control required for lateral balance during walking may be expected to elevate the attentional costs of walking.

In particular, we examined the effect of variations in lateral balance demands on attentional costs of walking in both young and older adults. Balance demands were manipulated by means of two levels of prescribed step width (SW; preferred vs. narrower than preferred, imposed by means of visual lines projected onto the walking surface) and a lateral stabilization device (involving two levels of mechanical stabilization (IJmker et al. 2013)). With these manipulations, we created conditions with higher and lower balance demands, respectively. The attentional costs associated with these conditions were assessed with vibrotactile stimulus-response reaction times (RT) (Peper et al. 2012; Mazaheri et al. 2014). We expected that higher balance demands (as evoked by walking with a narrow base of support) would increase the attentional costs of walking, particularly in older adults. Likewise, we expected that lower balance demands (as evoked by lateral stabilization) would reduce the attentional costs of walking, again particularly in older adults.

MATERIAL AND METHODS

Participants

Twenty young adults (female/male: 12/8) and 20 healthy older adults (female/male: 12/8) participated in the experiment (Table 3-1). Participants had no self-reported cardiovascular or cardiopulmonar problems, orthopedic conditions, uncorrected visual or auditory impairments, neurological disease, or other conditions limiting mobility; they did not use walking aids and the Mini Mental State Exam score for the older participants exceeded 24 (range 24-30). All participants provided written informed consent before participation. The departmental ethics committee approved the experiment.

Table 3-1. Participants' demographic and clinical characteristics per group

	Young adults (f/m: 12/8)	Older adults (f/m: 12/8)	Group comparisons	
			Statistics	*p*-value
Age (yr)	23.2±3.3	72.9±4.6	t_{38}=39.13	<.001
Height (cm)	174.5±9.6	170.9±10.2	t_{38}=1.15	.26
Weight (kg)	64.6±10.8	66.6±10.2	t_{37}=0.60	.56
CWS (km/h)	4.2±0.6	3.7±0.7	t_{38}=2.43	.02
FRD (cm)	35.2±7.6	29.4±6.1	t_{38}=2.64	.01
Baseline RT (ms)	233.5±25.0	297.3±31.8	t_{38}=7.05	<.001

Notes: Values are mean±SD. CWS = comfortable walking speed; FRD = Functional Reach Distance; RT = reaction time; f/m = female/male.

Experimental set-up

The experimental set-up was designed to induce higher and lower balance demands, using two separate manipulations: prescribed SW and lateral stabilization. A force-platform instrumented dual-belt treadmill (ForceLink, Culemborg, The Netherlands) equipped with a projector allowing projection of visual lines onto the belt's surface was used to measure and impose SW in the prescribed conditions (Figure 3-1A). In the lateral stabilization conditions, an external stabilizer (IJmker et al. 2013) (Figure 3-1B) was used to enhance lateral stability. Two spring-like rubber cords were attached to a frame fastened to the waist and anchored to ball-bearing trolleys that moved freely in for-aft direction within a horizontal rail parallel to the ground, positioned at either side of the participant. The height of the rail was adjusted to the participant's waist height. Cords with two different levels of stiffness (low stiffness: 760 Nm^{-1} and high stiffness: 1613 Nm^{-1}, see (IJmker et al. 2013)) were used, with the high-stiffness level providing larger stability.

Stimulus-response RT was measured using a custom-made stimulus vibrator (pulse duration: 300 ms; attached to the non-dominant hand's wrist) and a response button (sampling rate: 1000 Hz; held in the dominant hand; (Peper et al. 2012; Mazaheri et al. 2014)). A safety harness to protect participants from falling was used in all walking conditions that did not involve the external stabilization frame.

A horizontally oriented tape measure attached to the wall at the height of the participant's acromion process was used in the Functional Reach Test (FRT).

Procedure

Preparation

Participants first practiced treadmill walking for 10 min. Next, comfortable walking speed (CWS) was determined by first increasing treadmill speed (in 0.1 km/h steps) until the participant reported his/her CWS was reached. After a 1.5 km/h increment, walking speed was decreased (0.1 km/h steps) until CWS was indicated again (Mazaheri et al. 2014). The average of these two subjective estimates served as the participant's CWS and was used for all subsequent walking conditions. Next, each participant's preferred SW at his/her CWS was determined (1 min).

Participants' balance ability was quantified as the functional reach distance (FRD) using the FRT (Duncan et al. 1990).

A

B

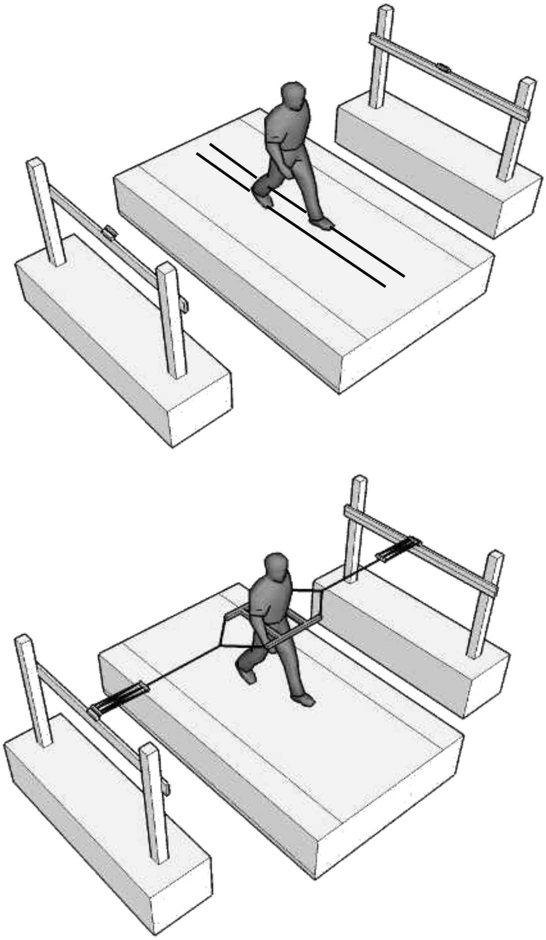

Figure 3-1. Schematic of the experimental conditions to vary lateral balance demands. (A) Walking on visual lines projected on the treadmill belt; (B) Walking with external lateral stabilizer with a spring-like cord attached to the light-weight frame fastened to the waist belt on one end and on the other end to the ball-bearing trolley. Figure adapted with permission from J Biomech 2013;46:2109-14.

Experiment

Participants walked under two prescribed SW conditions and two lateral stabilization conditions. For the prescribed SW conditions, the distance between the two visual lines projected on the treadmill belt's surface was set to 100% (preferred SW condition) or 50% (narrow SW condition) of each participant's preferred SW as determined in the pre-experimental trial. Participants were instructed to align the midline of their shoes with the visual lines. The lateral stabilization conditions involved walking with either low- or high-stiffness stabilizers. In these conditions, no visual lines were presented. Participants were familiarized with walking on the visual lines (1 min) and walking with the lateral stabilizer (5-10 min) prior to the corresponding experimental trials.

During each walking trial RT was assessed using 21 vibratory stimuli. To control gait cycle effects on attentional costs (Lajoie et al. 1993; Lajoie et al. 1996), RTs were presented at the moment of heel strike of either the left or right foot (equally distributed, random order) (Mazaheri et al. 2014). The first stimulus served as warning cue and appeared at least 5 seconds after the trial had started. Inter-stimulus intervals varied randomly between 3 to 17 seconds. Participants had to press the button as soon as they felt the vibration, but were asked to prioritize the walking task (Woollacott and Shumway-Cook 2002).

The experiment consisted of two blocks, which were counterbalanced across participants: one with prescribed SWs (preferred and narrow), the other with lateral stabilization (low and high stiffness). In each block, conditions were presented in random order, with two consecutive trials per condition. In addition, each block comprised one control condition involving unconstrained walking, yielding five dual-task walking trials in total per block. Prior to the first and after the second block of trials an RT baseline trial was conducted, measuring RT while sitting on a chair. Two single-task unconstrained walking trials (i.e., without RT) were also conducted, one prior to the first sitting trial and one between the two blocks. All trials lasted 2.5 min. Sufficient rest periods were administered between trials and blocks to prevent fatigue.

Data analysis

All data were analyzed using custom-made Matlab (Mathworks, Natick, MA, USA) scripts. The RT obtained for the first stimulus in each trial (warning cue) was eliminated, as were RTs <120 ms and >1100 ms (Mazaheri et al. 2014). Accordingly, 9 stimulus-response pairs were discarded in the older group (i.e. <0.01%; lateral stabilization: 2; prescribed SW: 7). No response was detected for 28 stimuli (i.e. <0.01%; young: 7, older: 21; predominantly for prescribed SW: 14). RT was defined as the median of the remaining time intervals between stimulus and response onsets per trial, and subsequently averaged over the two trials per condition. To eliminate individual baseline differences, attentional costs were characterized as difference scores ($\Delta RT=RT_{walking\ condition}-RT_{sitting}$) and proportional difference scores ($\Delta RT_{prop}=[RT_{walking\ condition}-RT_{sitting}]/RT_{sitting}$).

For each prescribed SW trial, the actually performed SW was determined from the force-plate data by taking the median of the absolute differences between left and right mediolateral center-of-pressure positions at mid-stance (i.e., halfway between foot contact and foot off). SW was averaged over the two trials per condition and normalized to the imposed SW. SW could not be reliably determined for one older participant in the imposed SW conditions because gait events were not well demarcated. For the unconstrained walking tasks, step width, stride length, stride time and cadence were determined.

Statistical analysis

Age, height, weight, CWS, FRD and baseline RT were compared between the two groups using independent *t*-tests. To examine the adherence to the imposed SW conditions, normalized SW was subjected to a 2 (group: young vs. older adults) by 2 (task: preferred vs. narrow SW) mixed-model ANOVA. The effects of age and lateral balance demands on ΔRT and ΔRT_{prop} were examined using 2 (group) by 5 (task: narrow SW, preferred SW, unconstrained walking, low-stiffness stabilizer, high-stiffness stabilizer) mixed-model ANOVAs. To examine whether the RT task affected gait, gait parameters were compared between unconstrained walking with and without RT, using a 2 (group) by 2 (task: with vs. without RT) mixed-model ANOVA. Alpha level was set at 0.05. Paired *t*-tests (with Bonferroni correction) were used for post-hoc pair-wise comparisons. Partial eta squared (η_p^2) and Hedges' g_{av} (g_{av}) were used to determine effect size (Lakens 2013).

RESULTS

Table 3-1 presents the participants' demographic and test characteristics. CWS and FRD scores were significantly lower in older adults. Baseline RT was significantly higher in older adults.

The ANOVA on normalized SW yielded a significant main effect of Task ($F_{1,37}$=244.94, p<.001; η_p^2=0.87): normalized SW was larger for the preferred SW condition than for the narrow SW condition (88%±9% vs. 55%±12%). The absence of a significant group effect ($F_{1,37}$=0.22, p=.64; η_p^2=0.01) or group by task interaction ($F_{1,37}$=0.72, p=.40; η_p^2=0.02) indicates that both groups adhered to the task in a similar fashion.

A significant main effect of Task on both ΔRT measures was observed (ΔRT: $F_{4,152}$=83.58, p<.001; η_p^2=0.69; ΔRT_{prop}: $F_{4,152}$=89.69, p<.001; η_p^2=0.70; Figure 3-2). Post-hoc analysis showed that ΔRT and ΔRT_{prop} were larger for the two prescribed SW conditions than the other three conditions (ΔRT: preferred SW: g_{av}'s>1.35; narrow SW: g_{av}'s>1.36; ΔRT_{prop}: preferred SW: g_{av}'s>1.23; narrow SW: g_{av}'s>1.19), whereas neither the two SW conditions (ΔRT: g_{av}=0.05; ΔRT_{prop}: g_{av}=0) nor the other three conditions (ΔRT: g_{av}'s<0.12; ΔRT_{prop}: g_{av}'s<0.08) differed significantly from each other. The main effect of Group (ΔRT: $F_{1,38}$=0.97, p=.33; η_p^2 =0.03; ΔRT_{prop}: $F_{1,38}$=1.38, p=.25; η_p^2=0.04) and the Group × Task interaction (ΔRT: $F_{4,152}$=0.80, p=.52; η_p^2 =0.02; ΔRT_{prop}: $F_{4,152}$=0.24, p=.92; η_p^2=0.01) were not significant.

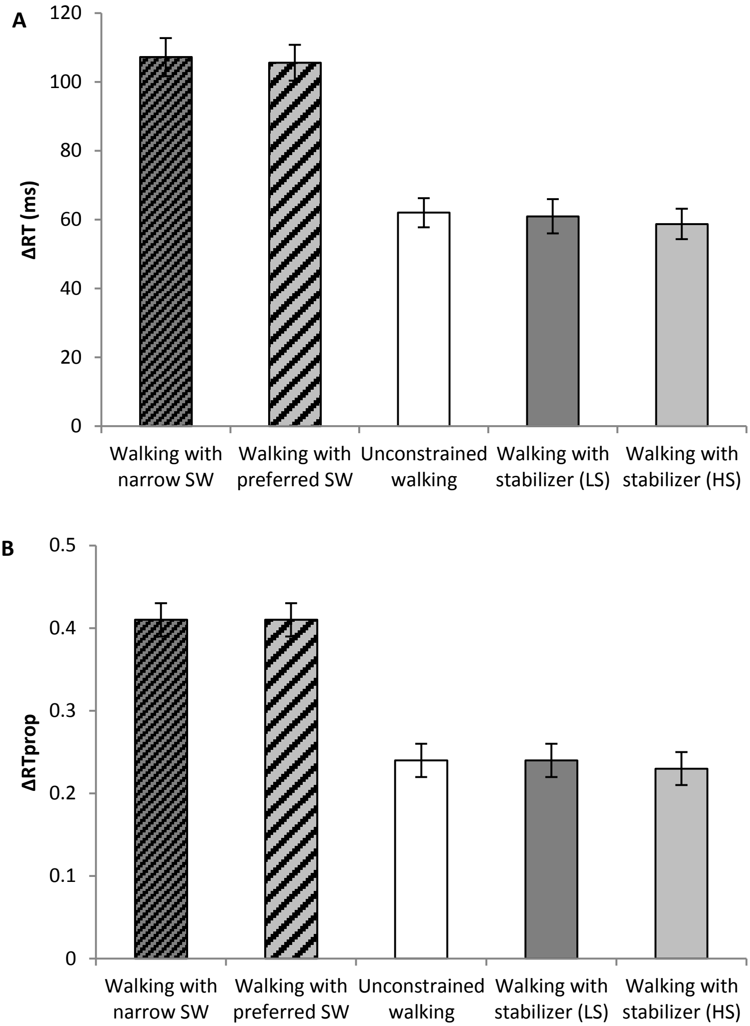

Figure 3-2. Mean ΔRT (panel A) and ΔRT_{prop} (panel B) for walking with narrow and preferred prescribed step widths, normal walking, and walking with low-stiffness and high-stiffness stabilizers. Error bars indicate standard error of the mean.

The ANOVAs on gait parameters as obtained for unconstrained walking (Table 3-2) revealed significantly wider SW and shorter stride length in older adults than young adults. Stride length and stride time decreased with dual tasking, whereas cadence increased.

Table 3-2. Effects of group and single vs. dual tasking on gait parameters

	Young adults		Elderly adults		Main effects		Interaction effect
	Single task*	Dual task*	Single task*	Dual task*	Group**	Task**	Group × Task**
Step width (m)	0.14 (0.03)	0.15 (0.04)	0.16 (0.02)	0.17 (0.02)	7.77 (**0.01**; 0.17)	2.40 (0.13; 0.06)	0.60 (0.44; 0.02)
Stride length (m)	1.28 (0.13)	1.25 (0.13)	1.12 (0.17)	1.11 (0.17)	9.99 (**<0.01**; 0.21)	28.73 (**<0.001**; 0.43)	2.87 (0.10; 0.07)
Stride time (s)	1.12 (0.10)	1.10 (0.09)	1.11 (0.12)	1.10 (0.14)	0.001 (0.97; 0.00)	16.46 (**<0.001**; 0.30)	0.54 (0.47; 0.01)
Cadence (steps/min)	108 (9)	110 (9)	109 (11)	111 (12)	0.04 (0.86; 0.001)	22.15 (**<0.001**; 0.34)	1.45 (0.24; 0.04)

* Values are presented as: mean (SD).
** Values are presented as: *F*-ratio (*p*-value; η_p^2). Significant *p*-values are presented in bold face.

DISCUSSION

We tested the assumption that the attentional costs of walking vary with lateral balance control requirements (Lajoie et al. 1993; Ebersbach et al. 1995; Lajoie et al. 1996) in a head-on fashion. We hypothesized that lower balance demands (lateral stabilization) would reduce the attentional costs of walking, whereas higher balance demands (narrow base of support) would increase the attentional costs. These effects were expected to be more pronounced in older adults.

However, the obtained ΔRT measures were not influenced by lowered balance demands: Walking with lateral stabilization did not result in lower ΔRT and ΔRT_{prop} compared to unconstrained walking, and neither did variations in stiffness of the stabilization device affect the ΔRT measures. Comparison between the two SW conditions (narrow vs. preferred) revealed no effect of increased balance demands on the attentional costs either, as the expected increase in ΔRT measures for the narrow SW condition was not observed. These results suggest that the contribution of balance control to attentional costs of walking was rather limited. Interestingly, however, the attentional costs increased when steps were adjusted to visual lines (i.e., in the prescribed SW conditions). In particular, the observed difference between unconstrained walking and walking on visual lines at the individual's preferred SW (i.e., the two conditions with comparable balance demands) indicated that the required visuomotor control in the latter situation resulted in elevated attentional demands. These results suggest that the attentional costs of walking depend more on visuomotor factors than on balance demands.

Our findings are not consistent with studies reporting variation of attentional costs with changes in balance requirements (Lajoie et al. 1993; Lajoie et al. 1996; Peper et al. 2012; Mazaheri et al. 2014). In those studies, base-of-support manipulations were used to vary balance demands (walking vs. standing or sitting; single-support vs. double-support stance phases), whereas in the present study the balance-demands manipulation was effectuated throughout the entire gait cycle. These differences hamper direct comparison with previous results.

The minor impact of lateral balance demands on attentional costs of walking may be related to the neurophysiological mechanisms underlying balance control. The presence of postural responses in decerebrated cats underscores the role of subcortical structures in mediating balance reactions, at least in mammals (Honeycutt et al. 2009). It has been suggested that this finding may be generalized to humans in view of a similar reliance of postural reactions on brain stem structures (Jacobs and Horak 2007). The subcortical nature of these mechanisms may explain why in our study lateral balance control during walking did not appear to affect higher-level cognitive processes associated with the RT task. In contrast, single-unit recording studies in animals showed more reliance on cortical activity (e.g. primary motor cortex) in Iocomotor tasks that are highly dependent on visuomotor processes, such as precision stepping (Armstrong 1988). Koenraadt et al. (Koenraadt et al. 2014) reported increased activity in the prefrontal cortex in humans during walking on visual targets compared to unconstrained walking. As this area is typically involved in complex gait tasks that are attentionally demanding, such as walking while talking (Holtzer et al. 2011), this observation suggests that visually guided walking requires more attention than normal walking. Indeed, larger RTs have been reported for visually cued walking than for unconstrained walking (Peper et al. 2012; Mazaheri et al. 2014), even if the unconstrained and visually imposed walking patterns were similar, indicating a relation between visuomotor demands and the attentional costs of walking (Bock 2008; Menant et al. 2014).

Our hypothesis that variation of lateral balance demands has a more pronounced effect on attentional costs of walking in older adults was not supported either. This absence of a group by task interaction may be related to the primarily subcortical nature of postural control. The finding that also the elevated attentional demands in the two SW conditions (involving enhanced visuomotor control) did not differ between the groups may be associated with the fact that participants walked at their preferred walking speed, which was slower in older adults (see Table 3-1). Reduced walking speed may reflect a conservative strategy adopted by older adults to preserve their limited attentional resources (indicated by lower baseline RT; cf. Table 3-1) for other tasks. Recent studies reported slower self-selected walking speeds in visuolocomotor situations (e.g., walking on a narrow path (Schaefer et al. 2015) or a sequence of stepping stones (Peper et al. 2015)) compared to unconstrained walking, for young and older adults alike. This was interpreted as an adaptive strategy to favor task performance relative to the visual context (Peper et al. 2015; Schaefer et al. 2015). Given our current results, it thus seems likely that older adults slowed down their preferred walking speed to increase the available time for visuolocomotor control (Maki 1997; Orcioli-Silva et al. 2012).

Because the absence of significant effects may be associated with limited sample size, we conducted a post-hoc power analysis for detecting a group by task interaction (Faul et al. 2007). Given our sample size (n=40), alpha level (0.05), and obtained interaction effect size (Cohen's d=0.14), the power to detect such an effect was 0.09. The required sample size to obtain power at the recommended level of 0.80 was 636, which would be exceptionally large for an experimental study like this. Another limitation of the study may reside in the reduced ecological validity of treadmill walking, which may have increased attentional costs, introducing the potential risk of a ceiling effect obscuring differences between conditions. However, the pronounced elevation of ΔRT measures in the prescribed SW conditions indicates that treadmill walking as such did not induce a ceiling effect for attentional demands. Another limitation relates to our decision to present RT stimuli at heel strike, whereas the more attentionally demanding single-support stance phase may have been more sensitive to condition or group effects (Lajoie et al. 1996). A final limitation is that dual-tasking effects on gait parameters were only examined for unconstrained walking. The RT task induced significant but small differences in stride length (2cm), stride time (20ms) and cadence (1 step/min), suggesting that the RT task had a limited effect on walking. This is consistent with other studies showing no (Lajoie et al. 1993; Lajoie et al. 1996) or negligible effects (Peper et al. 2012) of RT tasks on gait parameters under the instruction to prioritize the walking task. However, as we did not include single-task trials for the lateral-stabilization and imposed SW conditions (to limit the experiment's duration), it remains uncertain to what extent the prioritization instructions were successful in those experimental conditions.

In conclusion, our results indicate that, in healthy adults, attentional demands of walking were not influenced by variations in lateral balance demands. Perhaps the primarily subcortical nature of postural responses (Jacobs and Horak 2007; Honeycutt et al. 2009) requires minimal use of attentional resources. The higher attentional costs observed for walking on visual lines indicated that visuolocomotor demands contributed more to the attentional costs of walking than balance demands. The observation that the way in which ΔRT measures varied over conditions did not differ over the age groups may be associated with both the largely subcortical control of balance and the fact that both groups walked at their preferred walking speed (which was slower for older adults).

Chapter 4

Effects of age and dual tasking on step adjustments to sudden target shifts in visually cued walking

Mazaheri M, Hoogkamer W, Potocanac Z, Verschueren S, Roerdink M, Beek PJ, Peper CE, Duysens J. Effects of ageing and dual-tasking on step adjustments to perturbations in visually cued walking. Exp Brain Res 2015;233:3467-74.

ABSTRACT

Making step adjustments is an essential component of walking. However, the ability to make step adjustments may be compromised when the walker's attentional capacity is limited. The aim of the present study was to compare the effects of ageing and dual tasking on step adjustments in response to stepping target perturbations during visually cued treadmill walking. Fifteen older adults (69.4±5.0 yr; mean±SD) and fifteen young adults (25.4±3.0 yr) walked at a speed of 3 km/h on a treadmill. Both groups performed visually cued step adjustments in response to unpredictable shifts of projected stepping targets in forward (FW), backward (BW), or sideward (SW) directions, at different levels of task difficulty (which increased as the available response distance [ARD] decreased), and with and without dual tasking (auditory Stroop task). The results showed that in both groups, step adjustments were smaller than required. For FW and BW shifts, older adults undershot more under dual-task conditions. For these shifts, ARD affected the age groups differentially. For SW shifts, larger errors were found for older adults, dual tasking and the most difficult ARD. Stroop task performance did not differ between groups in all conditions. In conclusion, older adults have more difficulty than young adults to make corrective step adjustments while walking, especially under dual-tasking conditions. Furthermore, they seemed to prioritize the cognitive task over the step adjustment task, a strategy that may pose ageing populations at a greater fall risk. For comparable task difficulty the older adults performed considerably worse than the young adults, indicating a decreased ability to adjust steps under time pressure.

INTRODUCTION

The study of mechanisms behind the occurrence of falls in elderly has recently received a lot of attention. In an observational study, based on video footage of real-life falls, it has been shown that the most frequent cause of falling (accounting for 41% of falls) is an incorrect shift in bodyweight (including, for instance, misplaced steps during walking) (Robinovitch et al. 2013). This finding highlights the importance of assessing behaviors like step adjustments during walking, which are highly dependent on weight-shift strategies.

Step adjustments to sudden shifts in stepping targets have been studied extensively in relation to step initiation from standstill situations (Melzer and Oddsson 2004; Reynolds and Day 2005; Tseng et al. 2009; Melzer et al. 2010; Kim and Brunt 2013). This complex behavior requires two integrated motor skills: control of foot trajectory and control of balance (Reynolds and Day 2005; Tseng et al. 2009). While step initiation requires preplanning of foot placement and the associated postural adjustment, the shift of a stepping target after the step initiation stresses the need to modify these preplanned actions. Healthy young adults have shown fast and accurate step adjustments to unpredictable stepping-target shifts during step initiation without compromising balance (Reynolds and Day 2005; Tseng et al. 2009). However, this ability can be affected with increased age (Tseng et al. 2009; Young and Hollands 2012; Kim and Brunt 2013). That is, older adults have shown delayed onset of foot trajectory modification and prolonged execution time of the stepping limb in response to sudden stepping-target shifts during step initiation (Tseng et al. 2009). Tseng and colleagues (Tseng et al. 2009) related these deficits to degraded postural reactions of the contralateral leg, as evidenced by delays and decreases in the ground reaction force of the stepping response (see also (Kim and Brunt 2013)). Most of these deficits become more prominent with decreased available response time (Tseng et al. 2009; Kim and Brunt 2013). This means that in contrast to young people, older adults are less able to speed up reactive step adjustments under increased time pressure conditions (Tseng et al. 2009). These deficits might prevent timely step adjustments and their association with falls has been investigated previously. For example, Melzer and colleagues (Melzer et al. 2010) have shown that older recurrent fallers exhibit slower step adjustments compared to older non-fallers.

The aforementioned findings, however, are related to step initiation when stepping targets are suddenly perturbed in medial and/or lateral direction. As most falls occur during walking (Robinovitch et al. 2013), these step initiation experiments hardly reflect the step adjustment behaviors required during walking. Recent studies on walking adaptability or gait adaptability, i.e. the ability to adjust walking to meet task goals and environmental demands (Houdijk et al. 2012; Balasubramanian et al. 2014), presented visual context onto a walking surface in the form of obstacles (Potocanac et al. 2014) or stepping targets

(Mazaheri et al. 2014). In this way, step adjustments can be elicited by introducing shifts in stepping-target locations in different directions under various time pressure conditions (Bank et al. 2011; Peper et al. 2012; Young and Hollands 2012), which allows examining the ability to make step adjustments during walking. Another factor that limits the generalizability of step adjustment experiments (in both stand-still and walking situations) to real-life situations is their focus on single-task conditions while in reality step adjustments often occur while attention is shared with a secondary task, such as talking. The effect of a concurrent attention-demanding task on voluntary step initiation (with no target shift) has been examined in previous studies (Melzer and Oddsson 2004; St George et al. 2007). It was concluded that older people, in particular those at risk of falling, have an impaired ability to make accurate voluntary steps, especially when performing a dual task concurrently. To our knowledge, no studies to date have determined the effects of a concurrent attention-demanding task on step adjustments in response to sudden stepping-target shifts during walking.

Therefore, this study was designed to investigate the effect of age and dual tasking on step adjustment in response to unpredictable stepping-target shifts in different directions (i.e. forward, backward or sideward) under various time pressure conditions during visually cued treadmill walking. The feasibility of such tests was demonstrated in previous studies (Bank et al. 2011; Peper et al. 2012; Hoogkamer et al. 2015). In the current study, the step adjustment task was performed with and without an auditory Stroop task (which served as a concurrent attention-demanding task). The primary outcome measure was the step adjustment error, whereas the accuracy and reaction time on the Stroop task served as important secondary outcome measures for exploring task prioritization effects. It was hypothesized that all outcome measures would deteriorate with increased task difficulty (i.e., with increased time pressure demands). Moreover, it was expected that dual tasking has a detrimental effect on the step adjustments and that this influence is more prominent in older adults than in young adults.

MATERIALS AND METHODS

Participants

Fifteen healthy older adults (female/male: 10/5; mean±SD age: 69.4±5.0 yr; weight: 67.6±6.9 kg; height: 165.2±7.4 cm) and fifteen young adults (female/male: 10/5; age: 25.4±3.0 yr; weight: 66.3±9.0 kg; height: 173.0±8.2 cm) participated. Participants had no self-reported cardiovascular or cardiopulmonary problems, orthopedic conditions, uncorrected visual or auditory impairments, neurological disorders, or other conditions limiting mobility; they did not use a walking aid and were able to speak Dutch. All older adults had a Mini Mental State Exam score above 19 (actual range: 27-30). Thirteen older adults had no history of falls, one reported 1 fall and one reported 2 falls over the last year. The local ethics committee approved the experiment. All volunteers provided written informed consent before participating in the study.

Set-up

Participants walked on a force-platform instrumented treadmill (custom-built, ForceLink, Culemborg, The Netherlands) equipped with a projector and C-Mill software (Cuefors, ForceLink, Culemborg, The Netherlands), allowing the projection of stepping targets onto the belt's surface based on online detected gait events (using center of pressure (COP) data, sampled at 1000 Hz; (Roerdink et al. 2008)). In addition, reflective markers were attached to both shoes with two markers mounted on each shoe along the AP axis of the foot at heel side (at the approximate position of the calcaneal tuberosity) and toe side (at the approximate position of the 2nd toe) to record stepping errors relative to the projected targets, using a 10-camera Vicon motion capture system (Oxford Metrics Group, Oxford, UK) at 100 Hz. During the dual-task trials participants wore a headphone and a head-mounted microphone (wireless recording at 3000 Hz).

Procedure

Step adjustment task

Participants walked at 3 km/h on the treadmill[3]. The speed at which the stepping targets approached the participant was equal to the belt speed, which was constant across the experiment. The size of the stepping targets was adjusted to the participant's shoe length and width. The anterior-posterior (AP) distance between the stepping targets was attuned to the participant's preferred step length (determined by the C-Mill software from COP data (Roerdink et al. 2008) based on 20 seconds of uncued walking). The mediolateral (ML) distance between the stepping targets was 20 cm. The participants were instructed to place their feet as accurately as possible on the stepping targets. Every now and then, a stepping target would shift and participants needed to adjust their step to the new target location. These shifts targeted either the right or left leg, with 5-7 non-shifted targets in between the target shifts. Stepping stones were unpredictably shifted in different directions, i.e. forward (FW), backward (BW) or sideward (SW), in the same way as in Hoogkamer et al. (Hoogkamer et al. 2015). Longer-step responses were required for FW shifts, shorter-step responses for BW shifts and side-step response for SW shifts. The size of the stepping-target displacement was scaled to the individual's preferred step length: 40% for FW and

[3] To avoid confounding effects of speed on the manipulation of ARD and to be consistent with various previous studies (Hegeman et al. 2012; Potocanac et al. 2015), a fixed walking speed of 3 km/h was used.

BW shifts and 20% for SW (Figure 4-1). The smaller SW shifts were motivated by the observed preference for adjustments in the plane of progression as opposed to the frontal plane (Patla et al. 1999). Because lateral step adjustments are more successful than medial ones (Moraes et al. 2007), the SW shifts were presented in the lateral direction only. The stepping-target shifts occurred when the approaching stepping target came within a threshold distance from the participant's COP. This 'available response distance' (ARD) was set to 130%, 110% or 90% of the preferred step length and the lower it was, the more difficult the task was. These individualized ARDs were selected based on success rates during previous experiments using the same experimental setup (Potocanac et al. 2014; Hoogkamer et al. 2015).

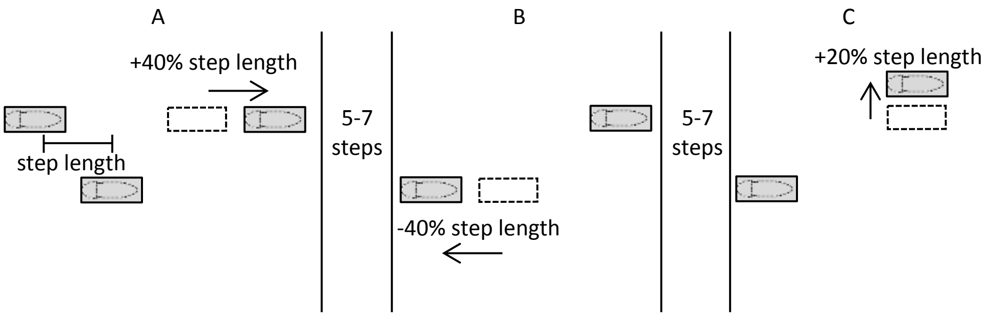

Figure 4-1. Schematic of the stepping-target shifts in the three directions. The distance between the stepping targets was determined based on participant's preferred step length. At a random time instant, a single stepping target (indicated by dashed squares) was shifted in either forward (size: 40% step length), backward (size: 40% step length) or sideward (size: 20% step length) direction which required, respectively, a longer-step (panel A), a shorter-step (panel B) or a side-step (panel C) response. The shift targeted either the right or left leg. At least 5 and at most 7 non-shifted stepping targets were presented between the shifted targets.

Auditory Stroop task

Through the headphone a series of "high" and "low" words spoken in Dutch was presented, in either high-pitched or low-pitched voice (McClain 1983). Both congruent (where the word and the vocalized pitch matched) and incongruent (where the word and the vocalized pitch differed) stimuli were presented randomly with an inter-stimulus interval of 1.6 s. The participants were asked to name the pitch of the voice as accurately and as quickly as possible (recorded by means of the microphone).

Protocol

Participants were first familiarized with treadmill walking for 5 min. After determination of preferred step length, participants were gradually introduced to the experimental tasks by means of walking on a series of 20 stepping targets presented to cue the steps of both legs without target shifts and then on a second sequence of 120 stepping targets, of which 18 (9 per leg) shifted in different directions.

The experiment consisted of two blocks (single task and dual task), each comprising 3 step-adjustment ARD conditions (130%, 110% or 90% of preferred step length), which were presented randomly within both blocks. Each ARD condition involved 60 shifted stepping targets of which 20 (10 per leg) shifted in FW, 20 (10 per leg) shifted in BW and 20 (10 per leg) shifted in SW direction. The shift directions were randomly distributed within each trial. The single-task block was presented first and, after a 10-minute break, participants were gradually prepared to perform the second block in which the walking task was performed concurrently with the auditory Stroop task. In preparation for the dual-task block, participants were first acquainted with the auditory Stroop task while seated. Further practice of the Stroop task was performed during walking on a series of 20 stepping targets followed by walking on a second sequence of 120 stepping targets, of which 18 (9 per leg) shifted in different directions. Additionally, the dual-task block included a condition of cued walking without stepping-target shifts, which served as the baseline condition for the auditory Stroop task. This condition was randomized together with the other conditions. In the dual-task conditions participants were asked to give equal emphasis to both tasks. The total experiment took about 2 h.

Data analysis

Stepping error was defined as the median of the AP distance (for FW and BW shifts) and ML distance (for SW shifts) between the center of shifted stepping target and center of the foot at midstance (at 50% of the time between heel strike and toe-off). The location of the center of each stepping target at midstance was available from the C-Mill software. The center of the foot at midstance was derived from the Vicon data. The foot was defined as the line connecting the reflective markers at the heel and the toe. The center of the foot was at 50% of this line. Stepping error was corrected for stepping bias by subtracting the distance between the foot and the stepping target at midstance of the last step before the shifted stepping target. Finally, the bias-corrected stepping error was normalized to each participant's preferred step length. Negative stepping error values indicated undershooting the shifted target.

The auditory Stroop task data were analyzed using a computerized analysis program (Potocanac et al. 2015), which was fine-tuned to a given participant's data. The software extracted the spoken words from the continuous audio recording of the trial by means of a threshold and recognized the content of the spoken words based on the Mel-frequency cepstral coefficients matched to Gaussian mixture models of signals for 'high', 'low' and noise made previously. Accuracy of the extracted word recognition, evaluated by 10-fold cross validation of a learning set, was 96%. Accuracy of the pitch analysis was 100%. Response latency was defined as the time between stimulus and response onsets. Mean response latency and mean percentage of accurate responses (%Accuracy) were determined for congruent and incongruent stimuli separately. All analyses were performed using Matlab 2011 (Mathworks, Natick, MA, USA). The data of one older participant were excluded from further analysis in view of a large number of incorrect responses due to insufficient understanding of the Stroop task.

Statistical analysis

Independent *t*-test was used to compare the preferred step length between the two groups. AP stepping error was analyzed using a 2 (group: young vs. older adults) × 2 (cognitive loading: single vs. dual task) × 2 (direction: FW vs. BW) × 3 (task difficulty: ARD 130% vs. 110% vs. 90%) mixed-model ANOVA with group as between-subject factor and cognitive loading, direction and task difficulty as within-subject factors. The stepping error for SW shifts was obtained in the ML direction and subjected to a separate 2 (group: young vs. older adults) × 2 (cognitive loading: single vs. dual task) × 3 (task difficulty: ARD 130% vs. 110% vs. 90%) mixed-model ANOVA.

Response latency on the Stroop task was analyzed using a 2 (group: young vs. older adults) × 2 (congruency: congruent vs. incongruent stimuli) × 4 (task difficulty: no-shift vs. ARD 130% vs. 110% vs. 90%) mixed-model ANOVA with group as between-subject factor and congruency and task difficulty as within-subject factors. Following logarithmic transformation to meet the assumption of normally distributed data, the same ANOVA was applied to the percentage of accurate responses. Significance was assumed for $p<0.05$. Post-hoc pair-wise comparisons were Bonferroni corrected.

RESULTS

Stepping error for forward and backward shifted stepping targets

The preferred step length was slightly lower for older adults (51.1±6.2 cm; mean±SD) than for young adults (54.1±3.2 cm), but this difference was not significant (t_{27}=1.63, p=0.12). Stepping errors were negative overall, implying that the shifted targets were undershot. For FW and BW shifts, the significant main effects of group ($F_{1,27}$=25.01, p<0.001), cognitive loading ($F_{1,27}$=11.38, p<0.01), direction ($F_{1,27}$=9.96, p<0.01) and task difficulty ($F_{2,54}$=118.78, p<0.001) implied a larger error for older adults, for dual-tasking, for BW shifts and for more difficult ARD, respectively. For older adults, the concurrent performance of the auditory Stroop task resulted in a larger stepping error compared to single-task conditions, whereas for young adults dual-tasking had no effect on stepping error (Figure 4-2, illustrating the significant group × cognitive loading interaction ($F_{1,27}$=7.30, p<0.05)).

Figure 4-2. Stepping error following FW and BW shifts (averaged over all difficulty levels) as obtained for the single-task and dual-task conditions in young and older adults. Stepping error values closer to zero indicate better stepping performance. Negative values indicate undershooting the shifted target. Error bars indicate standard error of the mean. Asterisks indicate significant differences.

The interaction of group × direction × task difficulty was also significant ($F_{2,54}$=9.02, p<0.001). Post-hoc analysis showed larger stepping errors for older adults compared to young adults in both directions and at all difficulty levels. Young adults made smaller step adjustments (i.e., larger errors) to BW shifts compared to FW shifts in the most difficult tasks (ARD 90% and 110%) (Figure 4-3, panel A), whereas for older adults this difference was only observed for the largest (least difficult) ARD (130%) (Figure 4-3, panel B). Furthermore, young participants' performance on BW shifts were more adversely affected by increasing task difficulty compared to FW shifts (Figure 4-3, panel A). For them, stepping errors to BW shifts increased significantly from ARD 130% to ARD 110% to ARD 90%, whereas for FW shifts only ARD 90% differed significantly from the other difficulty levels. In contrast, in older adults the increased stepping error induced by a decrease in ARD was more prominent for FW shifts than for BW shifts (Figure 4-3, panel

B). For older adults, the changes in stepping error from ARD 130% to ARD 110% to ARD 90% were all significant following FW shifts, while for BW shifts only ARD 90% differed significantly from the other two difficulty levels.

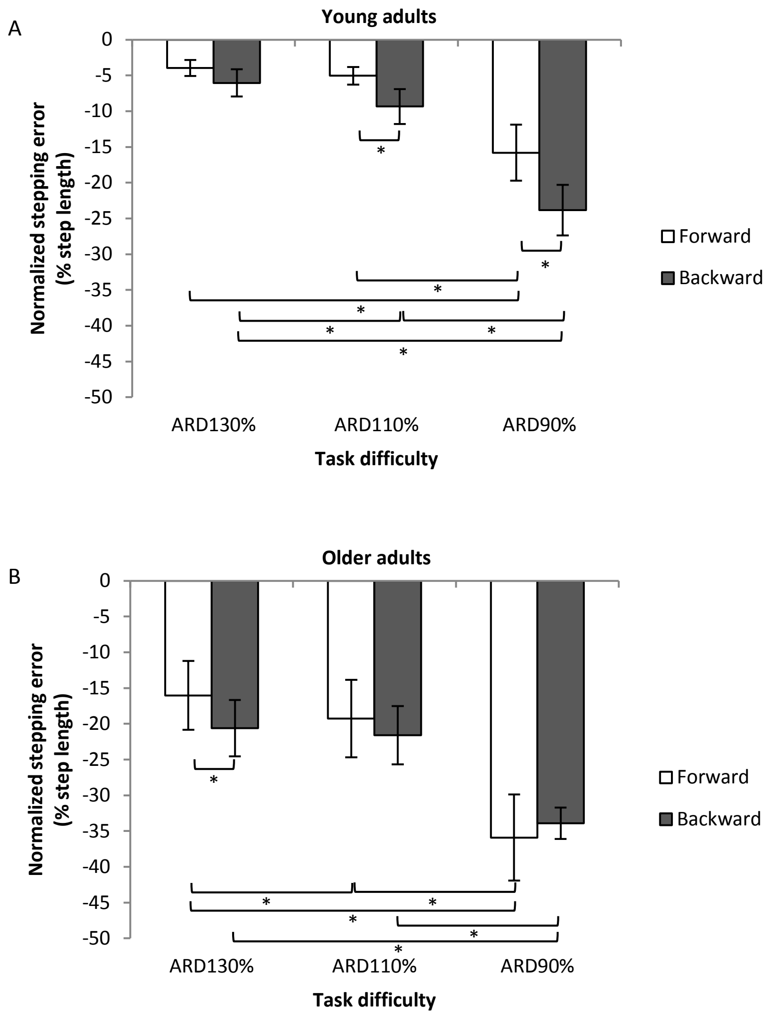

Figure 4-3. Stepping error following FW and BW shifts across the three levels of ARD as obtained for young (panel A) and older (panel B) adults.

Stepping error for sideward shifted stepping targets

The ANOVA on stepping error in response to SW shifts showed significant main effects of group ($F_{1,27}$=23.63, p<0.001), cognitive loading ($F_{1,27}$=14.83, p<0.01) and task difficulty ($F_{2,54}$=55.89, p<0.001). Stepping errors were negative overall, implying that the SW shifted targets were undershot. Stepping errors were larger for older adults (-8.7±5.8%) compared to young adults (-2.3±3.5%) and for dual-task conditions (-6.2±5.9%) compared to single-task conditions (-4.7±5.4%) (Figure 4-4). Larger errors were found for the most difficult level of ARD (90%: -8.5±5.8%) compared to the other two levels (110%: -3.8±4.9%; 130%: -3.9±5.1%).

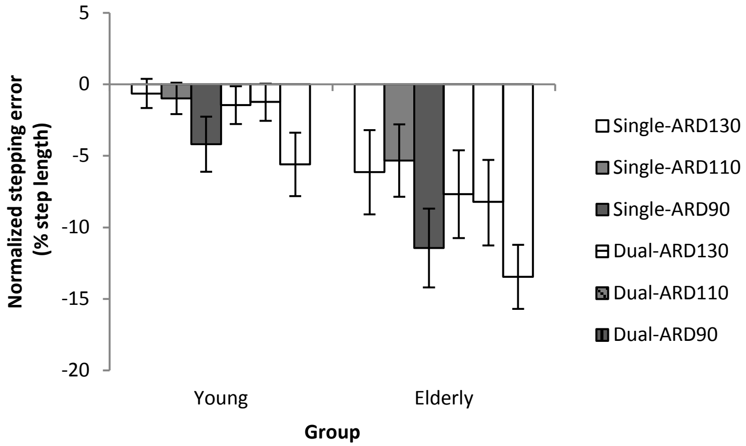

Figure 4-4. Stepping error following SW shifts across the three levels of ARD in young and older adults. See text for a specification of the statistical results.

Auditory Stroop task performance

The significant main effects of task difficulty ($F_{3,81}$=8.64, p<0.001) and congruency ($F_{1,27}$=35.25, p<0.001) indicated longer response latencies for the two most difficult levels of ARD (90%: 803±115 ms; 110%: 787±108 ms) compared to the baseline no-shift condition (742±105 ms) and for incongruent (807±113 ms) compared to congruent (747±101 ms) stimuli. Main or interaction effects involving the factor group were not significant.

For the percentage of correct responses (%Accuracy), significant main effects of task difficulty ($F_{3,81}$=5.52, p<0.01) and congruency ($F_{1,27}$=7.88, p<0.01) were found, indicating deteriorated performance with the most difficult ARD level (90.7±11.0%) compared to the two least difficult levels (baseline: 94.2±10.7%; 130%: 93.3±10.9%) and with incongruent (89.6±13.8%) compared to congruent (95.9±4.4%) stimuli. Again, main or interaction effects involving the factor group were not significant.

DISCUSSION

In the present study, step adjustments were elicited by means of sudden positional shifts of stepping targets during visually cued treadmill walking. Both age groups could perform this task successfully, although the step adjustments were smaller than the actual target shifts. For shifts in FW and BW direction, this effect was further exacerbated in older adults if they concurrently performed an auditory Stroop task. Whereas for the older participants step adjustment performance significantly decreased as a result of dual tasking, this was not the case for the young participants (Figure 4-2). Since the performance of the Stroop task did not differ between the two age groups, this result suggested that the older adults prioritized the auditory Stroop task over the step adjustment task, despite the explicit instruction to give equal emphasis to both tasks. This observation is at odds with the 'posture-first' principle (Bloem et al. 2001), according to which individuals prioritize walking over other concurrent tasks in challenging situations. Such optimization of walking at the expense of a secondary task is frequently observed in young adults (Bloem et al. 2006) and is an effective strategy to avoid falls. In contrast, our older adults appeared to be less inclined to use this strategy. They sacrificed their performance on the walking task in order to improve their cognitive task performance. The decline of this 'posture-first' strategy may pose ageing populations at a greater risk of falling in complex multitask environments (Bloem et al. 2006; Schaefer et al. 2015). Although this result seems to contradict previous work on obstacle avoidance (Potocanac et al. 2015), it is useful to note that the cost of failing to avoid an obstacle (possibly resulting in tripping and falling) is much higher than the cost of missing a shifted stepping target during visually cued treadmill walking. This difference suggests task-dependency in the adherence to the posture-first principle.

In this context it is useful to note that the apparent absence of a posture-first strategy may have been the result of a parsimonious attempt to simply ignore the shifted targets, so as to be accurate on all subsequent unshifted targets (i.e., the vast majority of stepping targets). In this way, essentially no step adjustment is required, instead of two (first to step on the shifted target, and then back to step on the subsequent unshifted targets). Perhaps, older adults adopted such a strategy, which would be consistent with the observed large undercorrection, especially under dual-task conditions (Figure 4-2). If so, then this strategy may still classify as posture first.

Effective use of step-lengthening and step-shortening strategies to overcome challenges in the environment has been shown to be a critical determinant of safe walking (Chen et al. 1994). The current stepping error results for FW and BW target shifts showed differences between the two age groups with respect to the two types of step-adjustment strategies. In young participants, the stepping error to FW shifts was smaller than their stepping error to BW shifts at all ARD levels, implying that longer-step strategies were more effective than shorter-step strategies. This result corresponds to the findings of Hoogkamer et al. (Hoogkamer et al. 2015), who also observed that, in response to target shifts, longer-step adjustments were performed more successfully than shorter-step and side-step adjustments. In the obstacle-avoidance literature, the advantage of the longer-step strategy over the shorter-step strategy has been discussed from various perspectives (e.g. time constraint, energy expenditure and biomechanics) (Chen et al. 1994; Weerdesteyn et al. 2005). From a biomechanical point of view, step lengthening has been considered as stabilizing and, consequently, regarded as a safer strategy. The observation that the shorter-step adjustments (BW shifts) decreased steadily (larger error) with increasing task difficulty (smaller ARD), whereas for longer-step adjustments (FW shifts) the decrease was only significant for the condition that was most time critical (ARD 90%), suggests that the longer-step strategy is also more robust against adverse influences associated with time pressure.

In contrast, for the older adults the longer-step responses (FW shifts) were only more accurate (smaller error) than the shorter-step responses (BW shifts) when time pressure was low (ARD 130%) (Figure 4-3B). This supremacy of longer-step responses is consistent with the findings of Bank et al. (Bank et al. 2011), who showed more adequate corrections for step adjustments following phase-delay than phase-advance shifts (comparable to FW and BW shifts, respectively, in our study) in older adults. Interestingly, however, this difference was not observed in older adults for the more time-critical conditions of the current study. This result may be associated with a ceiling effect for stepping error in the BW shift conditions. Whereas for FW shifts stepping error increased steadily with increasing time pressure demands, for BW shifts stepping error in the two least time-critical conditions was comparable, suggesting that in these conditions the maximum level of accuracy had been reached. This ceiling effect may be associated with the biomechanical aspects mentioned above, and related to the observation by Chen et al. (Chen et al. 1994) that tripping occurred only when older subjects tried excessive step shortening in an obstacle-avoidance task. The steady increase in stepping error with increasing time pressure of FW shifts (involving longer-step adjustments) observed for the older participants was not found for the young participants. This result is in line with the findings of Chen et al. (Chen et al. 1994), who showed that older adults experienced more difficulty compared to young adults to adopt the longer-step strategy when avoiding suddenly projected obstacles under higher time pressure.

Our finding that stepping error following SW shifts was larger in older adults than in young adults is consistent with Young and Hollands (Young and Hollands 2012), who showed that older adults make smaller step adjustment than young adults in response to lateral perturbations during visually cued walking. They attributed this deficit to age-related deterioration of visuomotor processing. However, decreased lateral stability with ageing due to impaired neuromusculoskeletal function, like reduced hip abduction torque production and lateral trunk control (Mille et al. 2005), seems a likely contributing factor as well. In addition, we found that also for SW shifts the stepping error increased as a function of time pressure, consistent with the FW- and BW-shifts results (with largest errors for the shortest ARD), and that for both groups performance decreased when the cognitive task was performed concurrently.

One limitation of the study was that the single- and dual-task blocks were performed in a fixed order. We opted for this design feature to minimize the chance of demotivating effects (Potocanac et al. 2014; Potocanac et al. 2015) during the more difficult dual-task condition. Hence, we started the experiment with the easier single-task block followed by the more difficult dual-task block. This sequential design may have resulted in order effects, such as learning to perform the step adjustments. Hence, the effect of dual tasking on stepping error may be somewhat underestimated compared to a counterbalanced design. In addition, it is conceivable that the statistical results were affected by the limited sample size (15 persons per group). In particular, the absence of a significant difference between FW and BW shifts in older adults under higher time pressure conditions may be partly due to the limited sample size in combination with high variability of stepping error (especially for FW shifts). Finally, one may raise the question whether the step responses in the present study as obtained for visually cued treadmill walking are similar to those occurring in uncued walking. Visual attention to the area of landing could be different. In future experiments it would therefore be useful to add an uncued walking condition in which only the to-be-shifted target appears from time to time. On the other hand, the current protocol has ecological validity since cued walking does occur naturally, for example as when walking between patches of rain and deciding to adjust foot placement at the last instance (Moraes and Patla 2006).

In conclusion, we have demonstrated several age-related differences in step adjustments in response to sudden target shifts during visually cued walking. Compared to young adults, older adults made smaller step adjustment in response to FW and BW shifts under dual-task conditions, yielding larger stepping errors. In contrast to the posture-first principle, they appeared to sacrifice stepping performance in order to preserve their performance on the cognitive task, at least if one focuses on the stepping error for the shifted targets only. This prioritization of the cognitive task at the expense of the walking task may result in increased risk of falling in older adults in daily-life dual-tasking conditions (e.g., talking on a mobile phone when walking).

Chapter 5

General discussion

Ageing is associated with a decline in the quality of walking. In particular, walking adaptability and balance control are typically compromised in older adults. However, little is known about how these components of locomotor control are linked to attentional aspects of walking. The research presented in this thesis aimed at examining the effects of age, adaptive stepping and balance control on the attentional costs of walking. Ageing effects with respect to task prioritization were also assessed for adaptive walking tasks with concurrent performance of an attention-demanding auditory Stroop task. Adaptive stepping was examined during visually cued walking with irregularly spaced stepping targets or with stepping targets that could suddenly shift. Lateral balance demands were manipulated by letting participants walk with a narrow step width (to increase balance demands) and with an external stabilization device (to decrease balance demands). Attentional cost was determined using a probe reaction-time (RT) task. Task prioritization was explored by examining dual-tasking effects on the accuracy of step adjustments and on the response latency and accuracy of auditory Stroop task performance. The main findings were as follows: (a) walking was more attentionally demanding for elderly than for young participants; increased adaptive stepping task demands induced increased attentional costs in young adults; elderly, especially those with lower executive function, did not invest extra attentional resources to deal with increased adaptive stepping task demands, which may have been associated with an already strong(er) reliance on visuomotor control (invoking elevated attentional demands) of uncued walking; (b) attentional costs were influenced more by visuomotor demands than by balance control demands; (c) older adults had more difficulty than young adults in making corrective step adjustments, particularly so during concurrent Stroop task performance; they seemed to prioritize the Stroop task over the step adjustment task. Collectively, these findings suggest that elevated attentional costs in older adults are related to elevated visuomotor demands of walking and that older adults use suboptimal task prioritization during adaptive stepping.

In this final chapter, I will discuss these main findings in relation to the modified tripartite model, as presented in the Introduction (See Figure 1-2), followed by an outlook for future research.

Attentional costs of adaptive stepping

The results of Chapter 3 indicated that the attentional costs of walking are influenced substantially by visuomotor demands, as walking on visual lines turned out to be more attentionally demanding than normal walking. However, unlike young adults, older adults did not demonstrate a substantial increase in attentional costs with increased complexity of visually guided walking (Chapter 2). Given the age-related increase in attentional costs during uncued walking, this finding may indicate that in older age the attentional efforts for visuomotor control during normal walking are increased to the level required for regularly cued walking in young adults. The relation between visuomotor demands and attentional costs of walking has previously been underscored by increased age-related dual-task costs for tasks that are highly dependent on visual processing (Bock 2008; Beurskens and Bock 2013). For instance, walking combined with a visually demanding non-walking task (such as a visual checking task) accentuated dual-task deficits in older age (Bock 2008). This effect was even more pronounced when walking on a visually demanding narrow path or obstacle path (Beurskens and Bock 2013).

Age-related differences in eye movements and gaze behavior may partly explain the changes in visually guided walking and the associated attentional costs in older adults. Old age is characterized by increased latency, duration and inaccuracy of saccadic eye movements (Irving et al. 2006). Several studies have shown that older adults are different from young adults with respect to when and where they look at future target locations during visually guided walking (Chapman and Hollands 2006; Keller Chandra et al. 2011; Yamada et al. 2012). If the foot has to be positioned on a target very accurately, older adults look significantly sooner to future stepping targets and fixate stepping targets longer than young adults (Chapman and Hollands 2006). Other studies showed that during both obstacle avoidance and foot placement on a target, older adults fixate their gaze closer to the imminent obstacle (Keller Chandra et al. 2011) or target (Yamada et al. 2012). Older adults have also been found to show delays in saccadic reactions in response to visually guided step adjustments (Young and Hollands 2012). These changes in gaze behavior may be maladaptive and hence may induce increased attentional demands. Older adults also show increased dependence on vision during walking (Anderson et al. 1998), perhaps due to deterioration of proprioceptive and vestibular inputs (Sloane et al. 1989; Shaffer and Harrison 2007). This might be another reason for the increased attentional costs of walking in older adults.

Attentional costs of balance control

The results of Chapter 3 revealed that attentional costs of walking were hardly affected by the imposed balance demands. This general finding indicates that in the modified tripartite model presented in Figure 1-2, the walking adaptability component makes a greater contribution to attentional costs of walking than the balance control component (Figure 5-1). This is in agreement with the original formulation of the model, in which 'attentional demand' was suggested to be a component of walking adaptability (Patla and Shumway-Cook 1999; Balasubramanian et al. 2014). Based on the current results, the greater contribution of walking adaptability to the attentional costs of walking seems largely attributable to attention-demanding visuomotor control processes inherent to walking adaptability tasks.

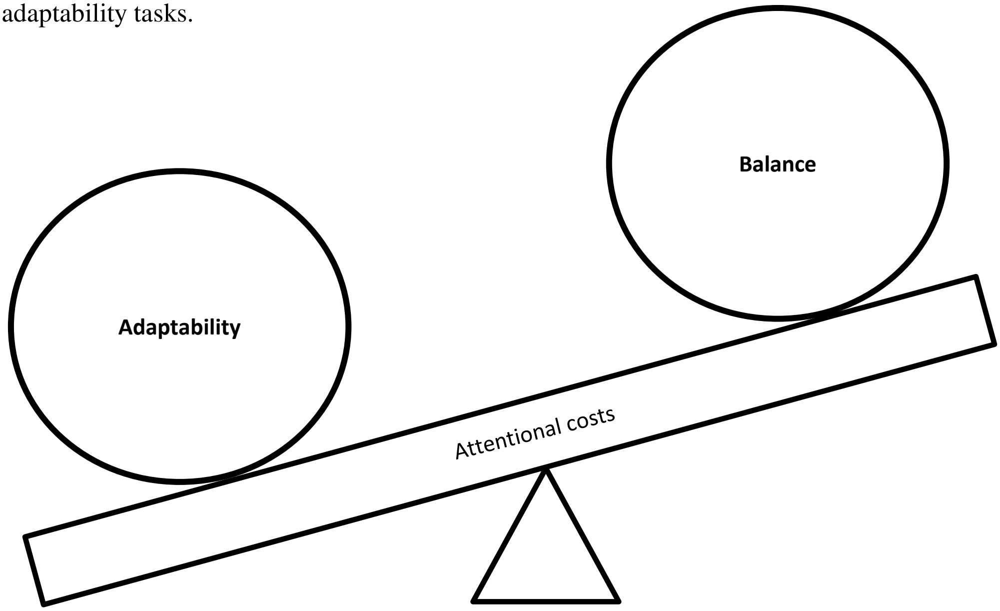

Figure 5-1. Contribution of walking adaptability and balance control components to attentional costs of walking

To interpret the aforementioned findings, it is useful to take into account the neuronal structures contributing to the control of adaptive stepping. Supraspinal control plays an essential role when adjustments in walking are required in response to particular features of environmental contexts (Armstrong 1988). Animal studies have provided evidence for the major contribution made by supraspinal structures to adaptive walking tasks, particularly those dependent on visuomotor control such as precision stepping (e.g. walking on a horizontal ladder (Armstrong 1988) or obstacle avoidance (Marigold et al. 2011)). However, research on the neuronal mechanisms underlying visuolocomotor control is limited. In an attempt to study cortical control of gait using a novel neuroimaging technique, namely functional near-infra-red spectroscopy (Koenraadt et al. 2014), it was found that precision stepping was associated with activation of the prefrontal cortex. The neuronal underpinnings of the increased attentional costs were partly revealed by showing that this region of the brain is more involved with allocation of attention to complex tasks, such as walking while talking (Holtzer et al. 2011).

It is generally assumed that attentional costs of walking vary with changes in balance requirements (Lajoie et al. 1993; Ebersbach et al. 1995; Lajoie et al. 1996). However, our experimental manipulations of lateral balance demands had no effect on the attentional costs of walking. A plausible explanation for this finding may be related to the neurophysiological mechanisms underlying balance control. Whereas cortical processes appear to play an essential role in visuolocomotor control, balance-related postural reactions may rely more strongly on subcortical structures. It has been shown that decerebrated animals are still able to produce muscle activation and force responses to support surface perturbations similar to those of intact animals (Honeycutt et al. 2009; Honeycutt and Nichols 2010). This highlights the important role of subcortical structures in mediating balance reactions required for balance maintenance in the presence of postural perturbations and may explain why lateral balance control manipulations in our experiment did not affect attentional costs (Chapter 3).

In this context it is important to realize that the null effect was obtained for manipulations of balance control in isolated conditions of elevated or lowered demands. The considerations above regarding the neurophysiological underpinnings of adaptive walking and balance control raise the question whether such a null effect would also be obtained in the context of walking adaptability, as step adjustments place strong demands on balance control. Reynolds and Day (Reynolds and Day 2005) studied gait initiation and step adjustment in response to sudden shifts of stepping targets in medial and lateral directions under two balance support conditions (with and without handrail support). Stepping targets were undershot, especially when no balance support was provided, highlighting balance as an important constraint on the accuracy of step adjustments. Similar difficulties in making step adjustments under increased balance demands were observed in stroke patients (Nonnekes et al. 2010). It is conceivable that the attentional costs of adaptive walking vary as a function of the associated balance control demands. Smulders et al. (Smulders et al. 2012) have shown that the attentional costs of obstacle crossing are higher for the crossing steps than for the pre-obstacle and post-obstacle crossing steps. Such findings suggest that extra balance requirements of obstacle crossing may contribute to the elevated attentional costs of the crossing step. Another indication that balance control during adaptive stepping is related to attentional costs can be found in the effects of walking adaptability training. After a period of walking adaptability training, people showed improved balance control (Heeren et al. 2013) and reduced attentional costs associated with obstacle avoidance steps (which may be related to a better dynamic balance and/or more automatized step adjustments) (van Ooijen et al. 2015). Hence, it would be worthwhile to focus future research on assessment of balance control in a more functional manner, which may shed a different (i.e. more task specific) light on its contribution to the attentional costs of (adaptive) walking.

Two other aspects that may be related to the obtained null effect of manipulated balance demands on attentional costs of walking are related to specific features of our experiment. First, it is possible that confounding effects were introduced by the use of the external stabilizer (IJmker et al. 2013). The set-up used in Chapter 3 not only stabilized the pelvis in mediolateral direction but also imposed constraints on pelvic rotation around the vertical and anteroposterior axes, which may have affected the gait pattern. Hence, it is not improbable that the external stabilizer interfered with other aspects of walking than balance demands alone. The problem of constrained pelvic motion may be overcome by using an external stabilizer that restricts pelvic motion in the frontal plane while allowing pelvic rotations. Although the additional constraints imposed by the external stabilizer may have interfered with the intended manipulation of balance, this was the case for both stabilizer conditions that were compared to examine the effect of enhanced balance on the attentional demands of walking. Moreover, this interference does not provide an explanation for the fact that null effect was also obtained for the other manipulation of balance, by means of variations in step width.

The final aspect that immediately comes to mind when considering null effects is whether or not the sample size was sufficient for finding significant effects. In Chapter 3 post-hoc power calculation for finding significant effects of reduced balance demands on attentional costs of walking revealed that the sample size should be increased to 636 participants to reach a power at the recommended level of 0.80. With the current sample size, however, significant effects were observed in terms of a pronounced elevation of RT in the two imposed step-width conditions. This indicates that strong effects can still be revealed even with the modest sample used. Hence, the observed null effect in Chapter 3 for the reduced balance demands was likely a genuine effect and probably not just caused by a limited sample size only.

Task prioritization during adaptive stepping

Age-related dual-task ability has been measured in different ways. In some studies, participants were requested to prioritize one of the two tasks, and the dual-task effects are examined separately for each performance measure, i.e. primary and secondary task performance (Smulders et al. 2012). Other studies averaged performance changes over both tasks when performed simultaneously. As introduced by McDowd (McDowd 1986) and subsequently applied by Bock (Bock 2008; Beurskens and Bock 2013), dual-task costs (DTC) can be expressed by combining the performance on dual-task and single-task performance in a single measure: DTC = $\frac{D-S}{S}$, where D represents dual-task performance and S represents single-task performance. By averaging the DTC as obtained for each component task, the overall costs of dual tasking can be assessed. Note, however, that the overall score does not provide information on the question how tasks were prioritized. Task priority can be deduced based on DTC scores for both tasks.

In the study presented in Chapter 4, participants were instructed to give priority to both tasks. However, it is conceivable that people choose differently in real-life situations in which no explicit instructions are provided and where they are free to decide whether to give equal or different priorities. Given the elevated attentional demands of walking observed in older adults, it does not seem unlikely that they will opt for the latter possibility, which may result in a poorer motor performance, ranging from a minor deviation from normal walking to a complete arrest of walking ('stops walking while talking' as introduced by (Lundin-Olsson et al. 1997)). However, when people are walking on a motorized treadmill over which they have no control, it is not possible to stop walking. This implies that given the use of treadmill walking the present study did not provide the full range of possibilities for prioritization. On the other hand, the use of a treadmill offered a large advantage in prescribing a standard speed, allowing comparisons between subjects at the same walking speed.

Task prioritization can also be influenced by walking speed. The use of comfortable walking speed in Chapters 2 and 3 was motivated by the finding that attentional costs vary with walking speed, with the lowest costs occurring at one's preferred speed (Kurosawa 1994; McFadyen et al. 2009). In our studies comfortable walking speed was determined for unconstrained walking. However, self-selected walking speed is generally lower in the presence of visual stepping targets (Peper et al. 2015), which may be related to increased attentional costs associated with elevated visuomotor demands. Therefore, the relation between walking speed and attentional costs (Kurosawa 1994; McFadyen et al. 2009) should be considered as a potential complicating factor when studying task priority.

When two or more tasks are performed simultaneously, certain tasks may be prioritized. According to the 'posture-first' principle, both young and older healthy adults prioritize walking performance over the secondary cognitive task (Bloem et al. 2001; Bloem et al. 2006). However, the older adults in the study presented in Chapter 4 were less inclined to prioritize step adjustment performance over auditory Stroop task performance. This finding highlights that task prioritization is not invariant. It depends on the difficulty of the walking task and the cognitive task as well as on the experimental instructions. For instance, the prioritization strategy may have been different if our participants had been involved in a more challenging adaptive stepping task, like avoiding a physical obstacle. In the latter case, failure would result in a substantially higher risk than would poor foot placement on a shifted stepping stone. In such a situation, older adults may be forced to adopt a safer strategy, by prioritizing the adaptive stepping task over the concurrent cognitive task. Likewise, instructions with regard to prioritization typically affect the way in which attention is divided over the two tasks. Because in Chapters 2 and 3 the aim was to assess the attentional demands of specific walking conditions by means of a secondary RT task, we used clear prioritization instructions to let the participants focus on the walking task. Although dual-tasking was found to affect the gait pattern to some extent, the obtained differences were marginal indicating that the obtained variations in RT indeed reflected differences in the attentional costs of walking under the various experimental conditions.

Outlook

In situations that place high demands on adaptive walking, people are often warned to mind their step, which seems very appropriate given the poor task prioritization that we have observed in Chapter 4. A related typical warning is to watch out, stressing the importance of gaze strategies when walking in complex environments. Interestingly, for both obstacle avoidance and foot placement on a target, deviant gaze patterns have been observed in older adults as compared to young adults (Chapman and Hollands 2006; Keller Chandra et al. 2011; Yamada et al. 2012). Given the observed relation between visuomotor control and the attentional costs of walking, it is conceivable that such deviations in visual attention are related to elevated attentional demands. Young and Hollands (Young and Hollands 2010) showed that deviant gaze behavior in older adults was associated with degraded stepping behavior, and that gaze training (to adopt the gaze pattern that was observed for young adults) resulted in improved stepping. This suggests that the deviant gaze behavior in older adults is a maladaptive change, and it would be interesting to establish whether it is associated with the elevated attentional costs of visually guided walking in older adults.

Adaptive walking in older adults was associated with elevated attentional costs and different task prioritization compared to young adults. Future research may be directed at answering the question whether training can improve attentional costs of walking adaptability and whether such improvements can be made following single-task training or dual-task training. According to the ‘task integration hypothesis’, integration of two tasks requires dual-task practice, thereby improving dual-task performance (Kramer et al. 1995; Ruthruff et al. 2006). Studies targeting dual-task training in young adults indeed have shown a reduction of dual-task costs in obstacle-avoidance tasks (Worden and Vallis 2014). In this context, it is worth noting that variable-priority training (varying priorities between cognitive and motor task) is more effective than fixed-priority training (giving equal priority to both cognitive and motor tasks) in terms of long-lasting effects (Silsupadol et al. 2009). On the other hand, the ‘task automatization hypothesis’ suggests that single-task practice can reduce attentional demands (by automatizing task performance) and increase performance skills (Kramer et al. 1995; Ruthruff et al. 2006). For example, the research by van Ooijen et al. (van Ooijen et al. 2015) showed reduced attentional costs of obstacle avoidance after a period of (single-task) walking adaptability training in persons with stroke. However, it is still unclear which of these methods yields superior therapeutic effects, especially in ageing populations.

Conclusion

The results of the experiments presented in this thesis suggest that adaptive stepping increases attentional costs but substantially less so in older adults than in young adults. This is presumably due to already elevated attentional efforts for visuomotor control during normal walking to such an extent that further allocation of attentional resources to deal with increased task demands is limited. For the employed experimental manipulations, it seems that visuomotor demands contribute stronger to attentional costs of walking than balance demands. Finally, older adults seemed to prioritize the attention-demanding Stroop task over the step-adjustment task. Therefore, a warning to older adults to focus attention on where they are stepping seems appropriate. So, older adults: ‘Mind Your Step!’.

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Summary

Walking disorders represent a common health problem in older adults which increases with advancing age. Walking disorders are associated with falls and increased risk of certain diseases (e.g. cardiovascular disease) and dementia, which in turn lead to loss of independence and reduced quality of life. Understanding factors leading to walking problems is crucial for the prevention and treatment of walking disorders in ageing populations. Several studies have revealed that walking is an attention-demanding task. In many situations the attentional resources have to be shared with other tasks that are performed simultaneously (e.g. walking while talking); as a result, walking performance may deteriorate due to increased *attentional costs* and/or poor *task prioritization*. The attentional demands of walking increase with ageing, but little is known about the way in which attention is allocated to specific components of walking. According to the tripartite model of locomotor control, these components are adaptability, balance, and stepping. In this thesis the attentional demands of walking are studied in relation to the first two components of the tripartite model, i.e. *walking adaptability* and *balance control*. In particular, this thesis focuses on the effects of age, adaptive stepping, and balance control on attentional costs of walking and on the effects of age on task prioritization during adaptive walking tasks while concurrently performing an attention-demanding cognitive task. **Chapter 1** provides an overview of the main concepts, rationale, and objectives of the research reported in this thesis.

In the first experiment, described in **Chapter 2**, the effects of age, executive function and stepping-task complexity on the attentional costs of walking were investigated. A group of young adults and two groups of older adults (one with higher and one with lower executive function) walked on a treadmill at their self-selected comfortable walking speed under three conditions: uncued walking and walking onto a sequence of regularly or irregularly spaced visual stepping targets projected onto the treadmill belt. A probe reaction-time task was used to measure attentional costs, which was normalized to baseline performance as obtained during sitting. Participants were required to give priority to the walking task. The attentional costs of uncued walking was significantly higher for older than for young participants. Increased stepping-task demands (as imposed by the visual stepping targets) induced different changes in attentional costs in the three groups. In young participants, the attentional costs increased significantly from uncued to regularly cued to irregularly cued walking. In older adults with higher executive function, attentional costs were significantly higher for irregularly cued than regularly cued and uncued walking. In the lower executive function group, however, no significant change in attentional costs was observed. The results indicated that older adults, especially those with lower executive function, did not invest extra attentional resources to deal with increased stepping-task demands. This may be attributed to already elevated attentional costs of uncued walking, which are presumably required for visuomotor and/or balance control of walking.

To test the interpretation proposed in the first study that attentional costs of walking may be associated with the attentional demands of balance control, the study in **Chapter 3** examined the effect of lateral balance demand manipulations on attentional costs of walking. Young and older adults walked on a treadmill at their comfortable walking speed and their lateral balance demands were manipulated by means of two levels of visually prescribed step width, preferred step width and 50% thereof (i.e. higher balance demands), as well as by means of a lateral stabilization frame with two levels of stiffness, low and high stiffness (i.e. lower balance demands). A control condition of unconstrained walking was also included. Similar to the first study, attentional costs were assessed during these five walking conditions using a probe reaction-time task, which was normalized to baseline (sitting) performance. Participants were instructed to give priority to the walking task. Both imposed step-width conditions were more attentionally demanding than the three other conditions, in the absence of any other significant differences between conditions. These effects were similar in the two groups. The results indicate that for either type of manipulation attentional costs were not influenced by lower or higher balance demands. Attentional costs were, however, profoundly influenced by presentation of visual lines suggesting a considerable contribution of visuomotor control processes to the attentional costs of walking.

Whereas Chapters 2 and 3 focused on the attentional costs of walking under specific conditions, the experiment in **Chapter 4** addressed the effects of age and dual tasking on step adjustments to sudden target shifts in visually cued walking. Fifteen older adults and fifteen young adults walked on a treadmill belt augmented with stepping stones. While walking at 3 km/h, participants were required to make step adjustments in response to unpredictable shifts of stepping stones in forward, backward, or sideward directions and at different levels of task difficulty (which increased as the time pressure increased). Step adjustments were performed with and without an attentionally demanding auditory Stroop task. Participants were instructed to give equal priority to both tasks. Older adults made smaller step adjustments in response to forward and backward shifts under dual-task conditions. For these shifts, time pressure affected the age groups differentially. In contrast to young adults, in older adults the increased stepping error induced by an increase in time pressure was more prominent for forward shifts than for backward shifts. Stepping errors following sideward shifts were larger for older adults, dual tasking, and the highest time pressure level. Both groups showed comparable Stroop task performance in all conditions. The results indicated that dual tasking had a more detrimental effect on step adjustments of older adults. This finding, in conjunction with the absence of a difference in Stroop task performance over groups, seems to indicate prioritization of the cognitive task over the step adjustment task in older adults. This type of task prioritization is not consistent with the safer ‘posture-first principle’ wherein individuals prioritize the walking task at the expense of concurrent task performance. In a more challenging walking adaptability task, like avoiding a physical obstacle, poor task prioritization may have severe consequences (e.g., a trip leading to a fall).

In the general discussion presented in **Chapter 5**, the results are discussed in relation to the tripartite model of locomotor control and suggestions for future research are presented. The observed smaller changes in attentional costs during visually guided stepping in older adults may be attributable to already elevated attentional costs of walking. Presumably these elevated attentional costs are associated with enhanced visuomotor demands of walking in older adults. In attempting to explain these increased attentional costs of walking in older adults, it would therefore be informative to consider age-related differences in eye movements and gaze behavior, such as early gaze transfer from a target, or increased dependence on vision. Attentional costs of walking were more profoundly influenced by visuomotor demands than by balance demands. However, in the current study the contribution of balance demands to the attentional costs of walking were only examined for unconstrained walking and not for walking adaptability tasks. Since both balance and visuomotor control are central to walking adaptability, manipulating the demands associated with both factors during adaptive walking may shed a different light on their (relative) contribution to the attentional costs of walking. Finally, in the absence of prioritization instructions, older adults seemed to be more inclined to optimize their cognitive task performance at the expense of adaptive stepping task performance. Although the use of a treadmill with a fixed belt speed constrained prioritization possibilities (i.e., limiting participants to slow down or to stop walking as in 'stops-walking-while-talking'), older adults appeared not to opt for the 'posture-first' prioritization. In view of the identified poor task prioritization in older adults, 'Mind Your Step!' remains a good advice.

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از خانواده عزیزم که تمام تجربه های یکتا و زیبای زندگیم مدیون آنهاست، تقدیر می کنم. به خصوص از روح پاک پدرم که بزرگ بودنش و نسبت داشتنش با تمام افق های باز رمز موفقیتم شد؛ از مادرم، که وجودم برایش همه رنج بود و وجودش برایم همه مهر؛ از خواهر و برادرم که حس بودنشان شوق زندگی به من می دهد؛ از همسران شان به خصوص همسر خواهر که مراقبت بی نظیرشان از پدر در زمان بیماری مایه آرامش من بود؛ از رویا، بهاره، ندا، نوید و شیوا که خاطرات زندگیم با حضور شیرینشان رقم خورده است؛ و از رزیتا که با فکر زیبا و خلاق مشکلات مسیر را از آغاز تا پایان برایم تسهیل نمود.

About the author

CURRICULUM VITAE

Masood Mazaheri was born on 12 April 1977 in Isfahan, Iran. He received his Bachelor’s degree in Physical Therapy from Isfahan University of Medical Sciences, Isfahan (2001), his Master’s degree in Physical Therapy from Iran University of Medical Sciences, Tehran (2004) and his first PhD from University of Social Welfare and Rehabilitation Sciences, Tehran (2009). His research focused on *outcome measures in rehabilitation* and *posture assessment in patients with musculoskeletal disorders* (particularly low back pain). His research during this period has provided health practitioners with data regarding reliability, validity and responsiveness of the more prevalent outcome measures in rehabilitation and provided the field with a better understanding of the impact of musculoskeletal injuries on the relation between posture and cognition.

In 2009, Masood Mazaheri returned to his hometown to start his career as a university lecturer. His research at Isfahan University of Medical Sciences reached a milestone when he started to collaborate with several researchers at Vrije Universiteit Amsterdam in 2010 and 2011. This was initiated following his contact with Prof. Dr. Jaap van Dieen to discuss about collaborative projects on low back pain. This resulted in 3 full papers in international peer-reviewed journals.

From this collaboration, he learned that to ensure success of his end goal, i.e. improving mobility disorders, he needed multidisciplinary expertise to address more complex research questions. Therefore, he started his PhD fellowship in the field of *mobility and ageing* in the ‘MOVE-AGE’ program funded by the European Commission as part of the Erasmus Mundus program. The project was a collaboration between Vrije University Amsterdam and KU Leuven, resulting in the present thesis. In addition to working on his PhD project, Masood Mazaheri collaborated on research projects with other researchers from Vrije University Amsterdam.

LIST OF PUBLICATIONS

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Effects of ageing on the attentional demands of step adjustments to perturbations in visually cued walking. Accepted for oral presentation at International Society of Posture and Gait Research (ISPGR) world congress; 28 June-2 July 2015; Seville, Spain.

Are attentional demands of walking affected by variations in lateral balance? A comparison of young and older adults. Accepted for poster presentation at International Society of Posture and Gait Research (ISPGR) world congress; 28 June-2 July 2015; Seville, Spain.

Attentional allocation to visually guided walking depends on age and executive function. Poster presented at International Society of Posture and Gait Research (ISPGR) world congress; 29 June-3 July 2014; Vancouver, British Columbia, Canada.

PRIZES

Best Oral Presentation, MOVE-AGE Conference, 9-11 Sep 2015, Manchester, UK

2nd Best Researcher at the 1st Iranian Elite Scientific Competition in Europe, Russia and Commonwealth of Independent States, 2015

Outstanding Junior Researcher at the 18th National Razi Research Festival, 2013, Tehran, Iran. This festival is open to all Iranian medical professionals, with the junior researcher award reserved to those below the age of 35. Winners of this award are determined based on their exemplary publication record and the high impact of their published research, indicating that these researchers have had a significant impact on the entire medical field.

Best Researcher of Isfahan University of Medical Sciences in 2010, 2011 and 2012, Isfahan, Iran